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The Magellan Venus Explorer's Guide

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Cover: Magellan at Venus

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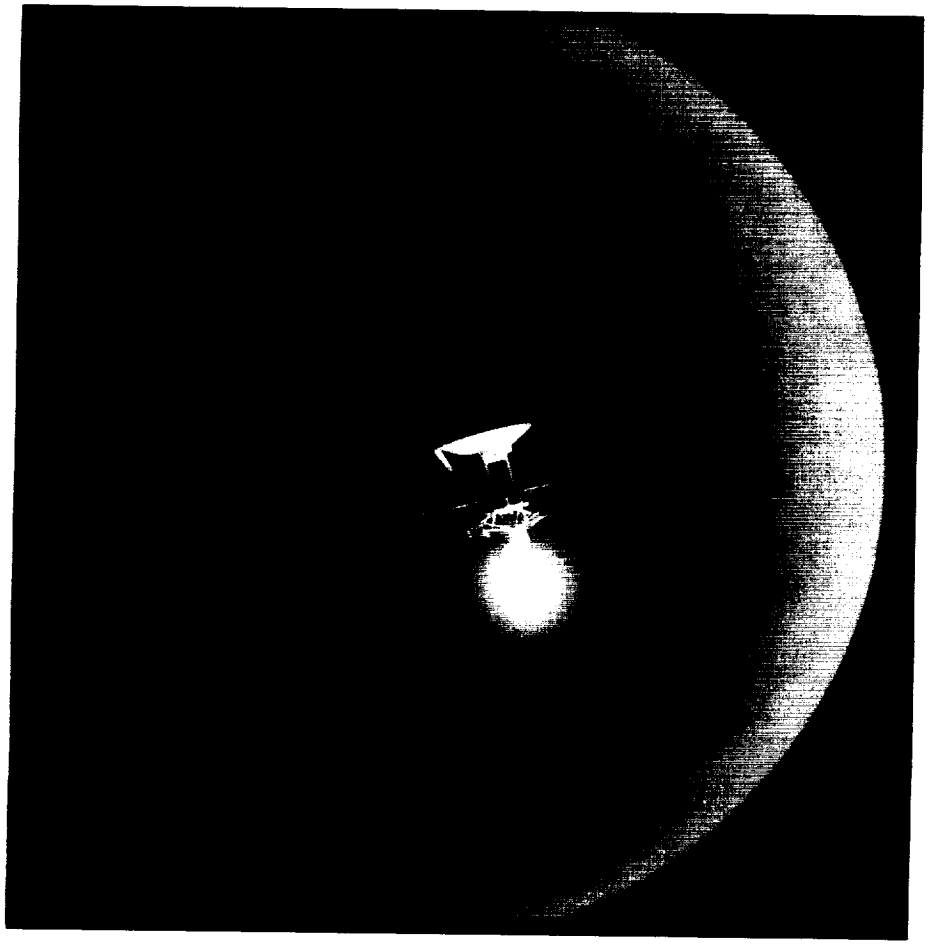

Around 9:30 a.m. (Pacific daylight time) on August 10, 1990, a powerful rocket thrust will begin the maneuver that will insert the Magellan spacecraft into orbit around the planet Venus. Since this event will take place "behind" the planet, as viewed from Earth, communications will be interrupted until the spacecraft emerges some 30 minutes later.

JPL Publication 90-24

The Magellan Venus Explorer's Guide

Carolynn Young, Editor

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Abstract

This publication describes the Magellan radar-mapping mission to the planet Venus. Scientific highlights include the history of U.S. and Soviet missions, as well as ground-based radar observations, that have provided the current knowledge about the surface of Venus. Descriptions of the major Venusian surface features include controversial theories about the origin of some of the features. The organization of the Magellan science investigators into discipline-related task groups for data-analysis purposes is presented. The design of the Magellan spacecraft and the ability of its radar sensor to conduct radar imaging, altimetry, and radiometry measurements are discussed.

Other topics report on the May 1989 launch, the interplanetary cruise, the Venus orbit-insertion maneuver, and the in-orbit mapping strategy. The objectives of a possible extended mission emphasize the gravity experiment and explain why high-resolution gravity data cannot be acquired during the primary mission. A focus on the people of Magellan reveals how they "fly" the spacecraft and prepare for major mission events. Special items of interest associated with the Magellan mission are contained in "windows" interspersed throughout the text. Finally, short summaries describe the major objectives and schedules for several exciting space missions planned to take us into the 21st century.

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Foreword

During the evening hours of August 9, 1990, the Magellan spacecraft will near the end of its 15-month journey to the planet Venus. By this time, the superior force of Venus' gravity becomes evident as the spacecraft begins a gradual, overnight acceleration that results in a more-than-twofold increase in its velocity.

By the morning of August 10, the Jet Propulsion Laboratory (JPL) in Pasadena, California, will be a hub of activity and anticipation as Magellan flies over the north pole of Venus, dives toward periapsis (closest approach) at 10°N latitude, rapidly decelerates from the powerful thrust of its solid-rocket motor, and maneuvers into an elliptical orbit around the planet.

After 3 weeks—during which time ground personnel will thoroughly examine the spacecraft and its single science instrument, a radar sensor—Magellan will begin the most comprehensive exploration ever undertaken of the surface of Venus.

The purpose of this Guide is to explain the objectives and some of the operations of the Magellan mission with what we hope are friendly terms and helpful illustrations. We'll take you on an imaginary tour of Venus and tell you what we have already learned about our sister planet from previous U.S. and Soviet missions and from ground-based observations. We think it is important that you become familiar with our planetary explorer, the Magellan spacecraft, and its radar sensor. By explaining some of the intricacies of synthetic-aperture (imaging) radar, we hope to increase your understanding of how this radar will provide the highest-resolution images ever obtained of the surface of Venus. Some historical facts about this long-awaited Venus mission are also included, along with information about the events that brought Magellan to the eve of Venus arrival and those events in the mapping operations that lie ahead. We also invite you to meet the people of Magellan and become familiar with some of the activities they perform.

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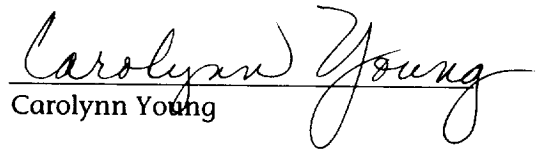
If we have an ulterior motive in writing this Guide, it is simply that you will be caught up in our excitement about the possibility of finding answers to the many questions about the surface features of Venus and the processes that have formed them.

The information provided is accurate as of mid-May 1990, when we had to stop writing and begin publication. In the interim, the last of three trajectory-correction maneuvers will be executed, and we have no reason to believe that it will be anything but successful.

When we began this Guide, a decision was made to use material that had already been written. Therefore, it is quite possible that some of you may recognize text that is your own. We ask you to consider our use of your words as a compliment and to know that we thought you said it best.



Carolynn Young

Table of Contents

1. INTRODUCTION 1

2. THE MAGELLAN MISSION 9

3. THE GEOLOGY OF VENUS 13
   - There are Many Unanswered Questions 13
   - A Few Words About the Mapping Phase 14
   - The Venus Coordinate System 14
   - A Tour Around Venus 16

4. THE MAGELLAN SPACECRAFT 51
   - Overall Physical Appearance 51
   - Spacecraft Equipment 57
   - Telecommunications 57
   - Attitude Control 60
   - Electrical Power 62
   - Command and Data Handling 63
   - Propulsion 63
   - Pyrotechnic Control 65
   - Thermal Control 65
   - Structure and Mechanisms 66
   - Computing and Software 67

5. THE RADAR SYSTEM 69
   - Understanding Synthetic-Aperture Radar 69
   - The Radar Sensor 73
   - Burst-Mode Data Collection 76

6. FERDINAND MAGELLAN—THE PROJECT'S NAMESAKE 81

7. THE SCIENCE INVESTIGATORS 85
   - The Radar Investigation Group 85
   - The Gravity Investigation Group 89
   - Guest Investigators 90

8. WHAT'S IN A NAME? 93

9. FROM EARTH TO VENUS 101
   - Launch 101

Magellan's Path to Venus 103
Back to the Drawing Board 107
Cruise Activities 107
Getting to Know the In-Flight Spacecraft 109
Planning for Orbital Operations 111
Practice Makes Perfect 112

10. IN ORBIT AT LAST! 113
Venus Orbit Insertion 113
In-Orbit Checkout 114

11. MAPPING THE VEILED PLANET 119
The Mechanics of the Mapping Pass 120
Alternate Mission Strategies 126
Extended Mission 128

12. GETTING THE JOB DONE 129
Planning and Coordination 129
Instructing the Spacecraft 131
Flight Operations 132
More About the Deep Space Network 133
Commanding 136
Receiving Data 137
The Mapping-Phase Data Flow 137
Processing the Data 138
Data Products 139
All Data Roads Lead to DMAT 141
Believe Us, There Is More 142

13. PROJECT ORGANIZATION 143
The Magellan Team 143
The Magellan Review Board 151

14. COMING ATTRACTIONS 153
Voyager Interstellar Mission 156
Galileo 158
Wide-Field/Planetary Camera—Hubble Space Telescope 160
Ulysses 162
TOPEX/POSEIDON 164
Mars Observer 166
Comet Rendezvous Asteroid Flyby 168
Cassini 170
Lunar Observer 172

Earth Observing System Synthetic Aperture Radar (EOS SAR) 174
Space Infrared Telescope Facility 176
Mars Exploration Initiatives 178
1998 Mars Global Network 180
2001 Mars Sample Return With Local Rover 180
2003 Mars Site Reconnaissance and Communications Orbiters 181
2005 Mars Rover 181
Mission Concepts 182
Solar Probe 182
Pluto Flyby 182
Rosetta: Comet Nucleus Sample Return 182
Mercury Dual Orbiter 182
Global Land/Ice Altimetry Mission 183
Submillimeter Imaging and Line Survey 183
Astrometric Imaging Telescope 183
Large Deployable Reflector 183

15. ACRONYMS 185

16. GLOSSARY OF GEOLOGICAL TERMS 189

17. ACKNOWLEDGMENT 197

18. MAP OF VENUS ..... Inside back cover

There was the Door to which I found no Key;
There was the Veil through which I might not see.

— Omar Khayyam

Chapter 1
Introduction

Exploration is the essence of the human spirit. The truth of this statement has been evident for as long as humans have inhabited Earth. For those whose curiosity extends to the other members of our solar family, another truth has been evident: our human spirit has been frustrated by Venus, our nearest planetary neighbor. For the last few centuries, dark clear nights and chilly morning hours have found us straining our eyes in the direction of this planet next door.

Just looking has taught us a lot. We have become aware of Venus' orbital motions around the Sun, its phases that are similar to those of the Moon, and the fact that Venus is the most like Earth in size, mass, and distance from the Sun. But the root of our frustration is the atmosphere of thick swirling clouds that perpetually hides the Venusian surface from view (see Figure 1-1).

However, a significant discovery was made in the 1940s that would eventually revive our sagging spirit: some radar waves are unaffected by clouds, yet are reflected by solid surfaces. By the early 1960s, radar-system facilities at Goldstone, California (Jet Propulsion Laboratory), Haystack, Massachusetts (Massachusetts Institute of Technology), and Arecibo, Puerto Rico (Cornell University), were, for the first time, able to identify persistent features in the radar data reflected from Venus. With

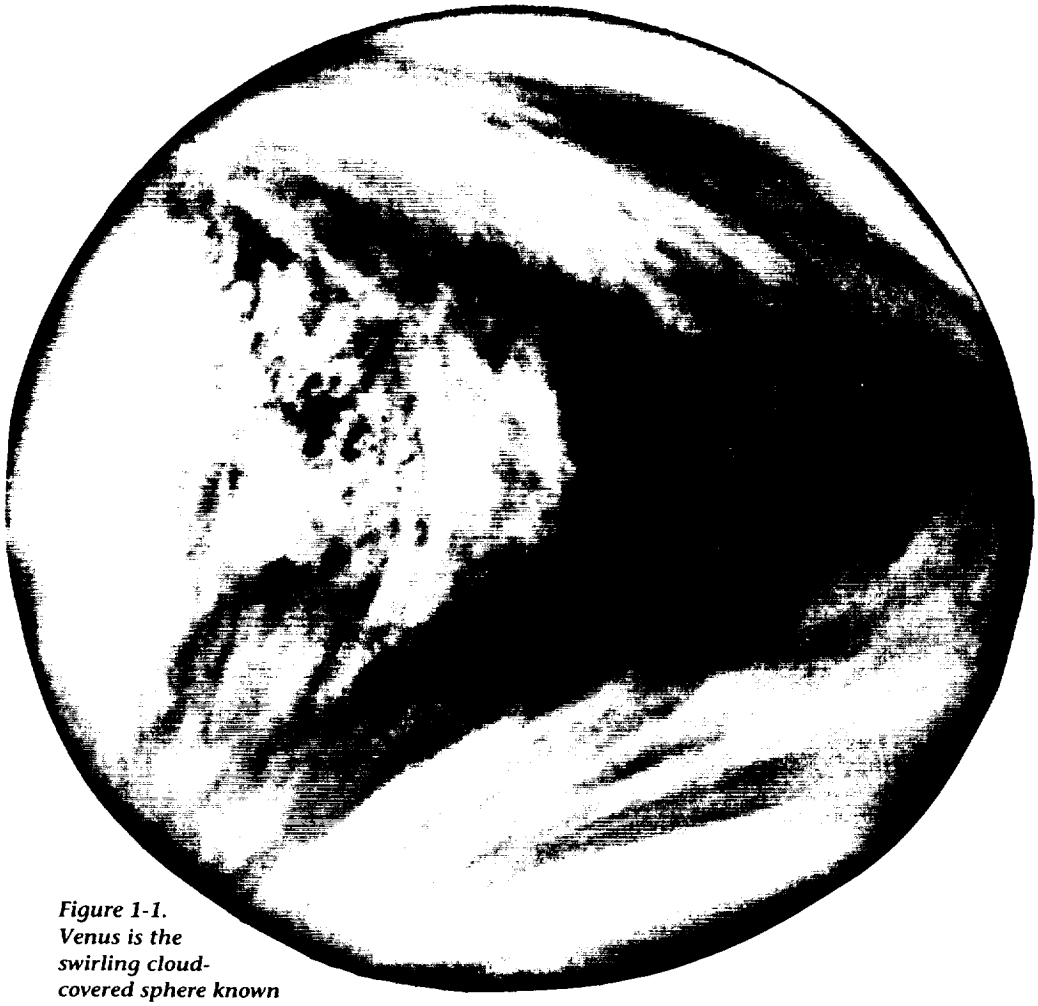


Figure 1-1. Venus is the swirling cloud-covered sphere known throughout history as both the evening and morning star.

the help of computer processing, crude images of the Venusian surface were produced. From these early studies, radar scientists computed the rotation rate of the planet, which is equal to 243 Earth days. They learned that this rate is much slower than that of the clouds, which the Mariner 10 mission in 1974 determined to be approximately 5 days. Another discovery revealed that Venus rotates in a retrograde direction, a direction opposite that of most of the other planets in the solar system. These radar studies also helped to refine our estimate of the distance between Earth and Venus and thus the astronomical unit (the average distance of the Earth from the Sun—about 150 million kilometers or 93 million miles).

Table 1-1. Venus Mission Chronology[a]

Mission	Launch Date	Description
Mariner 2 (U.S.A.)	8/27/62	Encountered Venus from 34,745 kilometers (21,594 miles) on 12/14/62; disclosed 468-degree-centigrade (900-degree-Fahrenheit) surface temperatures and absence of magnetic field.
Venera 4 (U.S.S.R.)	6/12/67	Relayed information on Venusian atmosphere for 93 minutes during entry on 10/18/67.
Mariner 5 (U.S.A.)	6/14/67	Flew within 4,023 kilometers (2,500 miles) of Venus on 10/19/67; furnished data on surface temperatures and atmospheric composition.
Venera 5 (U.S.S.R.)	1/5/69	Transmitted atmospheric measurements during aerodynamic and parachute descent on 5/16/69; confirmed high carbon-dioxide content and lack of water vapor.
Venera 6 (U.S.S.R.)	1/10/69	Similar to Venera 5; 5/17/69 entry date.
Venera 7 (U.S.S.R.)	8/17/70	First probe to soft-land on Venus; descended via parachute on 12/15/70; transmitted data for 23 minutes.
Venera 8 (U.S.S.R.)	3/27/72	Radioed surface temperature and pressure readings after landing on sunlit side of Venus on 7/22/72.
Mariner 10 (U.S.A.)	11/3/73	Encountered Venus on 2/5/74 en route to Mercury; tracked global atmospheric circulation with visible and ultraviolet imagery.
Venera 9 (U.S.S.R.)	6/8/75	An orbiter-lander similar to Venera 8; lander returned first panoramic view of surface.
Venera 10 (U.S.S.R.)	6/14/75	An orbiter-lander similar to Venera 9; lander transmitted panorama of landing area; sent back surface data for 65 minutes.
Pioneer 12 (U.S.A.)	5/20/78	Braked into Venus orbit on 12/4/78; performed detailed radar mapping of the planet's surface; discovered rift valleys and 11-kilometer- (7-mile-) high Maxwell Montes.
Pioneer 13 (U.S.A.)	8/8/78	Four instrumented probes entered Venusian clouds on 12/9/78; obtained temperature and pressure readings and data on wind patterns.
Venera 11 (U.S.S.R.)	9/9/78	A flyby-lander; descent vehicle soft-landed on 12/25/78; detected electrical and acoustical events in the atmosphere; flyby vehicle served as relay station.
Venera 12 (U.S.S.R.)	9/14/78	A flyby-lander similar to Venera 11; landed on Venus on 12/21/78; imaging system failed to return photos.
Venera 13 (U.S.S.R.)	10/31/81	An orbiter-lander; touchdown on 3/3/82; relayed first color images of Venusian surface.
Venera 14 (U.S.S.R.)	11/4/81	An orbiter-lander; lander returned color imagery; drilled soil samples, and conducted seismic experiment.
Venera 15 (U.S.S.R.)	6/2/83	An orbiter only; provided radar mapping with 2- to 4-kilometer (1- to 2-mile) resolution.
Venera 16 (U.S.S.R.)	6/7/83	Similar to Venera 15; performed radar mapping and atmospheric analyses.
Vega 1 (U.S.S.R.)	12/15/84	Venus–Comet Halley mission; carried Venus descent vehicle and atmospheric balloon probe.
Vega 2 (U.S.S.R.)	12/21/84	Similar to Vega 1; both spacecraft carried multinational experiment packages.

[a] Courtesy of National Space Society.

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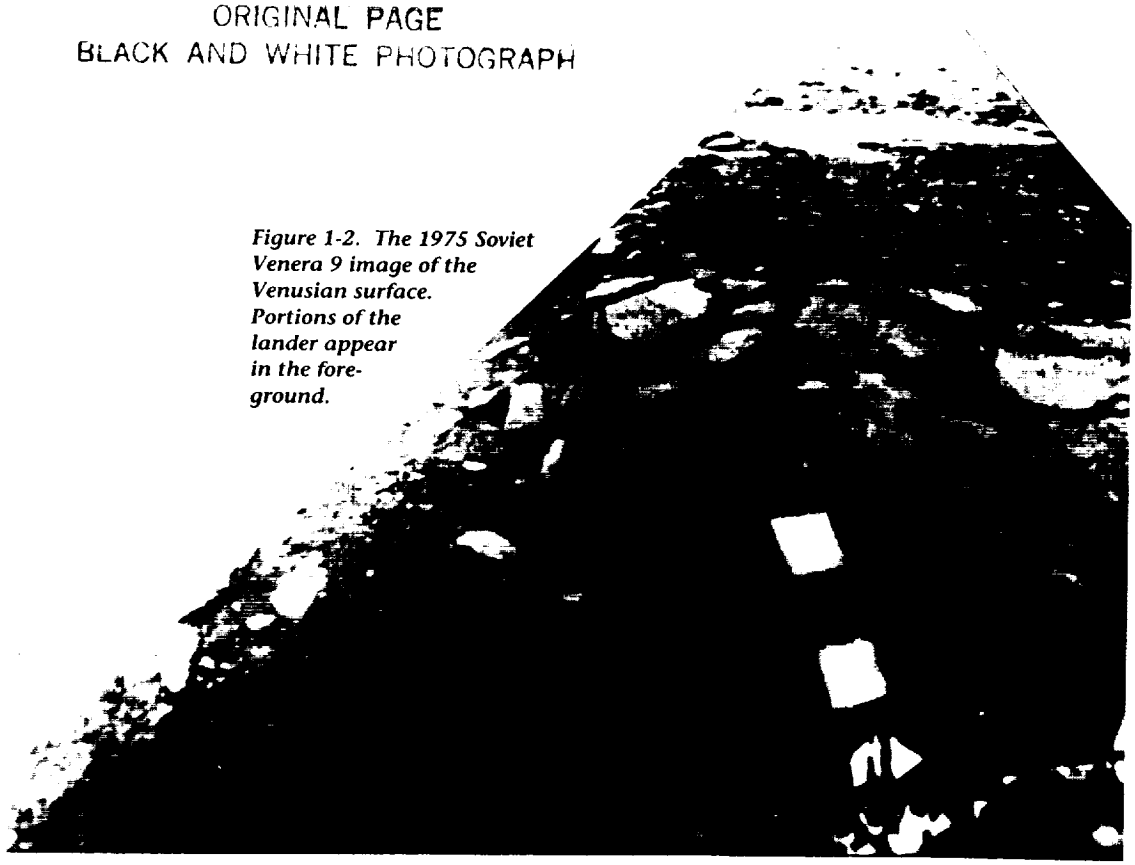

Figure 1-2. The 1975 Soviet Venera 9 image of the Venusian surface. Portions of the lander appear in the foreground.

Earth-based radar imaging is still a valuable tool in our continuing exploration of Venus. But it is also very limited. Venus always shows the same hemisphere to us when its orbit brings it near enough for the best observation, so only a fraction of the planet can be explored from Earth.

The early 1960s also brought about the use of spacecraft to explore Venus and, since that time, Venus has been one of the most visited planets in the solar system (see Table 1-1). Fifteen Soviet and five U.S. spacecraft have probed its sulfur-yellow clouds to measure atmospheric structure and composition. Other investigations disclosed a lack of water vapor and the absence of a magnetic field. Seven of the Soviet craft were landers that conducted chemical analyses of rocks, which indicated that some rocks were of volcanic origin. One of the landers, Venera 9, gave us our first glimpse of the surface when, in 1975, it relayed a panoramic view of the Venusian landscape (see Figure 1-2).

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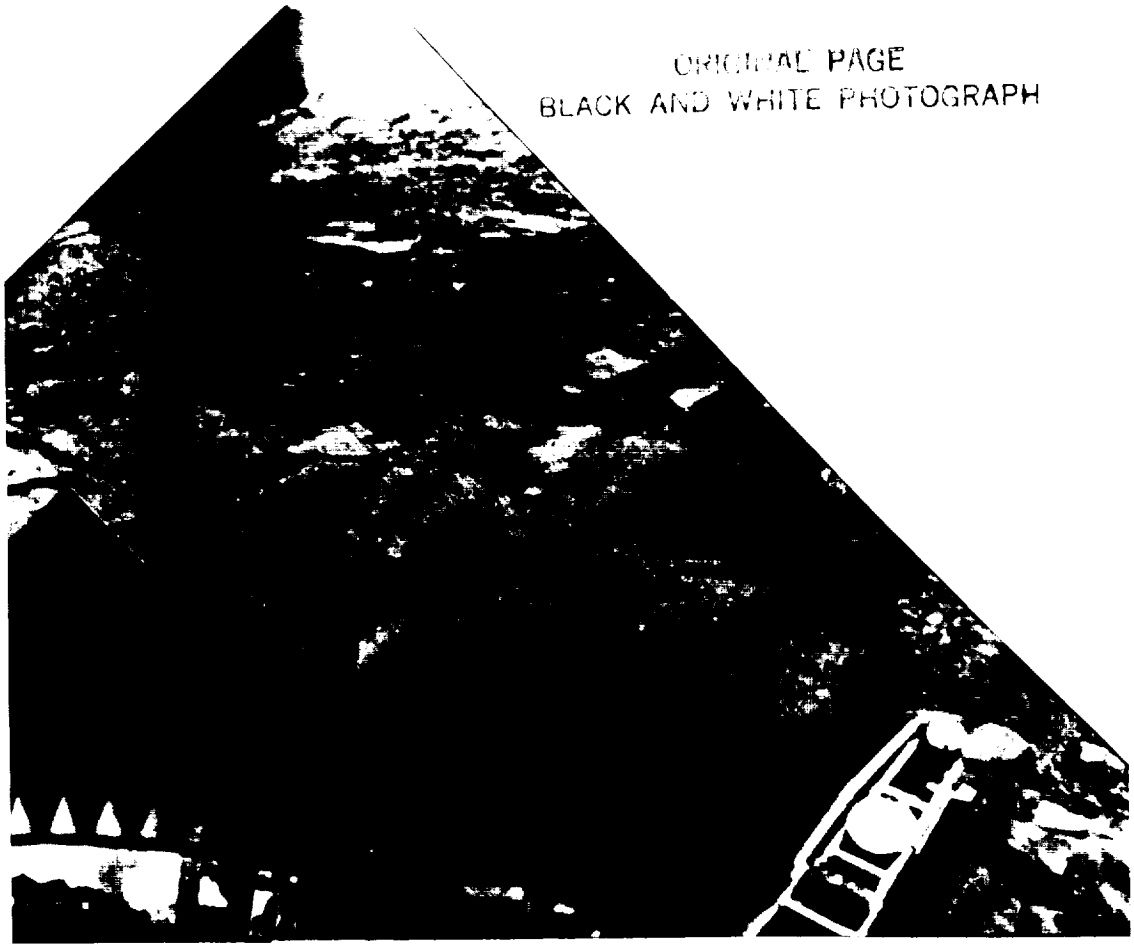

These discoveries were enhanced by observations in the field of radio astronomy, which indicated that Venus is a perpetual furnace, where surface temperatures reach 482 degrees centigrade (900 degrees Fahrenheit) and the atmospheric pressure is 90 times that of Earth.

The 1978 U.S. Pioneer Venus Orbiter (PVO) was the first spacecraft to carry a radar sensor to our sister planet. Ninety-two percent of the surface was mapped with a resolution (a measure of the smallest objects that can be seen in the resulting images) of 50 to 140 kilometers (31 to 87 miles). For the first time, planetary scientists had a global map of Venus. The existence of continentlike highlands, hilly plains, large volcanolike mountains, and flat lowlands was revealed.

Five years later, the Soviet Venera 15 and 16 spacecraft used radar to map about 25 percent of the northern polar region at a resolution of 1.2 to 2.4 kilometers (0.7 to 1 mile). These images revealed evidence of

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abundant volcanism, impact craters, complex tectonic deformation, as well as coronae—unusual, large, ovoidal features of apparent volcanic-tectonic origin (see Figure 1-3).

Yet, for all our accumulated knowledge about the atmosphere and the large-scale surface features, we know very little about the hills and valleys, craters, and lava flows—the telling details of Venusian geology.

Figure 1-3. The Venera 15 and 16 spacecraft revealed a number of features of unknown origin, such as Nightingale Corona, which measures approximately 560 kilometers (348 miles) in diameter. (The prominent dark line across the diameter of the feature is the result of gaps in the data.)

Figure 1-4. Magellan in orbit about Venus.

We wonder about the extent to which Venus' surface has been shaped by volcanoes, plate tectonics, impact craters, and water and wind erosion. Are the processes that produced the Venusian surface features still active?

The Magellan radar imaging spacecraft was launched from the Space Shuttle Atlantis on May 4, 1989, in search of the answers to these important questions. The spacecraft will maneuver into orbit around Venus on August 10, 1990 (see Figure 1-4). For the next 243 days (one Venus rotation), Magellan will gather radar imaging, altimetry, and radiometry data as it orbits the planet every 3.15 hours. Seventy to 90 percent of the Venusian surface will be mapped at resolutions that vary from 250 to 600 meters (800 to 2,000 feet), a view nearly 10 times better than that of any previous spacecraft. While Magellan sends data to Earth during each orbit, ground personnel will precisely measure slight changes in the spacecraft's orbital motion caused by variations in

Venus' gravitational field. These measurements will provide important clues about the nature of the planet's interior.

Magellan's innovative method of radar mapping, called synthetic-aperture radar (SAR), is key to fulfilling our long-awaited desire to unveil the secrets of our closest and most mysterious planetary neighbor.

It's a long road from the inception of a thing to its realization.

— Molière

Chapter 2
The Magellan Mission

In addition to its special contributions to science, the Magellan mission has a distinctive place in the current U.S. space program. It is the first planetary spacecraft to be launched by the shuttle, and it is the first of a series of missions resuming planetary exploration since the launch of the Pioneer Venus craft 12 years ago.

Magellan is named after the Portuguese explorer Ferdinand Magellan (see Chapter 6), whose expedition circumnavigated the world in the early 1500s. His journey revealed the vast nature of Earth and the distribution of broad oceans and continents. Similarly, the spacecraft Magellan is expected to provide a global understanding of the poorly known surface of Venus.

Concept studies of a radar-imaging mission to map the Venusian surface were begun by NASA in the early 1970s at JPL. The project was named Venus Orbiting Imaging Radar (VOIR), and science investigators were selected in 1979. However, VOIR was deemed too costly and was canceled in 1982. In October 1983, the Venus mission was reinstated as a NASA budgetary new start and named the Venus Radar Mapper (VRM), a reduced undertaking that eliminated all experiments except the gravity-field experiment and those involving the radar (which included imaging, altimetry, and radiometry). Also, to accommodate a

reinstatement proviso that the spacecraft be built for about half the originally estimated cost, VRM used mission-proven technologies and spare components from other flight programs such as Voyager, Galileo, and Ulysses. The major contractors selected for this JPL-managed mission were the Martin Marietta Astronautics Group in Denver, Colorado, for the spacecraft and the Hughes Aircraft Company of El Segundo, California, for the radar sensor. VRM was officially renamed Magellan in 1986.

Thus, with a scaled-down experiment package and with other compromises, such as the use of an elliptical orbit compared with VOIR's circular one, the Venus mission was on track again with a launch planned for May 1988.

Did you know . . .

The Magellan mission will generate more digital data than that of all previous U.S. planetary missions combined.

The Challenger disaster in 1986 caused another delay. The explosion led to the reevaluation and subsequent cancellation of the Centaur G-Prime booster as cargo on the shuttle. The most powerful upper stage ever designed, Centaur was to have propelled Magellan to Venus. Its explosive liquid-oxygen and liquid-hydrogen propellants, however, were deemed too dangerous to be carried in a manned space vehicle.

The U.S. Air Force's less-powerful Inertial Upper Stage (IUS) replaced Centaur as the booster for Magellan; this required some modification of the spacecraft designs and mission plans. The aluminum Centaur-adapter structure was replaced with a lighter, graphite-epoxy frame for the IUS. A lighter spring mechanism was also used to separate the less-massive IUS from the spacecraft after burnout.

The launch procedure was changed to deploy the solar arrays before ignition of the IUS because the booster's roll-control thrusters were too close to the ends of the solar panels while in their stowed (folded) position. Lastly, rather than subject the entire spacecraft to a repetition of full static tests in the new IUS configuration, a mockup Magellan structure was used. Fidelity was assured by using real components borrowed

from a Voyager spacecraft on public display at the National Air and Space Museum in Washington, D.C.

The loss of the Challenger and the 32-month suspension of shuttle missions delayed and reshuffled many planned space activities. The Galileo mission to Jupiter, for one, would have to launch in October 1989, the date initially set for Magellan, or wait another two years for the necessary alignment of planets. The result for Magellan was an early May 1989 launch and the use of a Type-IV trajectory. This meant that the spacecraft would spend 15 months traveling one and a half times around the Sun before arriving at Venus. The original May 1988 launch date would have allowed Magellan to reach Venus in 4 months by traveling less than 180 degrees around the Sun via a Type-I trajectory.

Thus, the $551 million mission (see Table 2-1) and the spacecraft that will soon arrive at Venus are much different than NASA had planned a decade earlier, yet the basic scientific mapping objectives remain unchanged.

Table 2-1. Magellan Costs

Item	$ M
Spacecraft (without radar)	287
Radar	120
Project cost through launch + 30 days	49
Mission operations/data analysis through end of the Project on 10/28/91	95
Total	551
Extended mission cycles through 1996	218[a]

[a] Not yet funded.

Man masters nature not by force but by understanding. This is why science has succeeded.

— Jacob Bronowski

Chapter 3
The Geology of Venus

The all-enveloping, continuous cloud cover around Venus has prevented optical imaging of the surface from spacecraft, which has slowed our understanding of its surface processes. The limited data we have acquired from spaceborne and ground-based observations, however, have been sufficient to indicate that the nature of the Venusian surface is indeed provocative.

There Are Many Unanswered Questions

When photo mosaics of the Magellan radar data are available to Magellan scientists, their eyes will eagerly search for details that may answer some very basic questions about the geology of Venus, such as

(1) What is the age of the surface?
(2) What geologic processes are dominant, and how do they relate to the activity within the planet?
(3) Is the surface shaped by plate tectonics, like that of the Earth's?
(4) What processes are responsible for erosion?
(5) Has the greenhouse effect always existed?
(6) Was there ever running water on the surface?
(7) What is the composition (i.e., rock vs. soil) of the surface materials?

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Of course, the most interesting answers may come from questions not even asked yet!

With the addition of gravity-field measurements, Magellan scientists hope to improve their understanding of the geophysics of Venus by determining how mass is distributed within the planet and by ascertaining the nature of the interior processes and how they affect the surface features.

A Few Words About the Mapping Phase

Magellan will maneuver into orbit around Venus on August 10, 1990. However, the mapping phase will not begin for 22 days. During that time, the spacecraft and the radar sensor will be tested and the orbit will be adjusted, if necessary. Magellan's orbit will be fixed inertially in space, which means the spacecraft will orbit the planet in a plane that is fixed, relative to the stars. Venus will rotate beneath the orbit of the spacecraft 1.5 degrees a day, or about 150 kilometers (93 miles). Thus it will take exactly one Venus rotation (243 Earth days) to conduct the mapping phase. The data will be acquired in strips about 25 kilometers (16 miles) wide and about 16,000 kilometers (10,000 miles) long, as the spacecraft moves from the north pole to about 74°S latitude.

Please note that . . .

The radar images in this chapter are oriented with north at the top.

The Venus Coordinate System

The map coordinate system used for measuring longitude on Venus is different from that used on Earth. On Earth, longitude (an imaginary line stretching from pole to pole) is measured from a starting point (the prime meridian) at Greenwich, England (near London), toward the east and toward the west with increasing values in degrees until east meets west at the 180-degree point (the dateline), which is diametrically opposed to Greenwich. On Venus, longitude is measured from 0 to 360 degrees with the prime meridian centered within a small impact crater named Ariadna, located in Sedna Planitia (see Figure 3-1). There is an

Figure 3-1. Sedna Planitia was imaged at the Arecibo Radar Observatory in Puerto Rico. Ariadna, the small circular feature surrounded by a bright halo in the southeast portion of the image, is an impact crater about 27 kilometers (17 miles) across. Image resolution is 2 to 3 kilometers (1 to 2 miles).

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arbitrary convention that determines the direction of increasing longitude on planetary bodies other than Earth: longitude shall be measured in a direction opposite to that in which the planet rotates. Because Venus rotates in a clockwise direction as viewed looking down on the north pole, longitude on Venus increases in numerical value toward the east from the planet's prime meridian.

A Tour Around Venus

For the remainder of this chapter, we will take an imaginary journey around Venus and discuss some of the important facts and questions about many of the surface features. So, before reading further, we suggest you remove the map of Venus from the inside back cover and navigate along with us. If you trip over some of the terminology, help is near at hand in Chapter 16, Glossary of Geological Terms.

Magellan will begin mapping at 307°E longitude over the western edge of Ishtar Terra, a highland region about the size of Australia (see Figure 3-2). During the next several weeks, a high volcanic plateau, called Lakshmi Planum, will be within view. Lakshmi is situated nearly 5 kilometers (3 miles) above the mean radius of Venus and is surrounded by mountain belts (ranges): Akna Montes (west), Freyja Montes (north), Maxwell Montes (east), and Danu Montes (south). All of these mountain belts show intense deformation (faulting and folding) of the planet's crust, similar to deformed rocks seen in mountain belts on Earth. Maxwell Montes contains the highest point on Venus; its peak towers more than 11 kilometers (7 miles) above the lowland plains. Two large volcanic calderas, Colette and Sacajawea, are located in the center of Lakshmi Planum and are surrounded by long volcanic flows. The origin of the high plateau and mountain belts is controversial. One theory suggests they formed over a hot plume of material rising from the interior of the planet, while another says the region is being compressed (pushed together) from all sides, resulting in material descending into the interior of the planet. Perhaps the Magellan images will reveal evidence of plate tectonics, a process that could have produced the large amounts of compression needed to form the mountain belts.

Lakshmi and its high mountains are surrounded by regions of tesserae terrain named Fortuna, Atropos, and Clotho Tesserae (also shown in Figure 3-2). Tesserae terrain, which was first detected by the Soviet Venera 15 and 16 spacecraft in the early 1980s, is characterized by complex intersecting ridges and grooves. This terrain may have been formed by large blocks of material sliding and collapsing down slopes, pulled by the force of gravity. In the extremely high-temperature Venus environment, rock can behave more like a fluid, unlike the rigid behavior of rocks found on Earth.

Magellan will next image Guinevere and Sedna Planitia (see Figure 3-1), south of Lakshmi Planum. These low-lying regions have abundant small volcanoes and long lava flows. We hope the lava flows will provide new and exciting information about the electrical properties of the materials that make up the surface of these plains. (Determining the electrical properties of surface material can tell us, among other things, the ratio of rock to soil.) Unlike similar plains on the Moon, Mars, and Mercury, the Venusian plains are relatively free of impact craters.

The Soviets have successfully landed several spacecraft in the plains regions. Seven of the landers conducted chemical analyses of rocks, which indicate a composition similar to that of terrestrial basaltic volcanic rocks. The Venera 9 lander gave us our first glimpse of the Venusian surface when, in 1975, it relayed the panoramic view shown in Chapter 1, Figure 1-2. In 1981, the Venera 13 lander provided the first color images of the surface of Venus. These photos from the Soviet landers are the only available local observations, and they will be most useful in interpreting the high-resolution Magellan radar images.

Moving now to the southern hemisphere, some of the first features that will be imaged are a group of high peaks called Ushas, Innini, and Hathor Montes (see Figure 3-3). These peaks are interpreted as being large shield volcanoes. Earth-based radar images show that the peaks are surrounded by lava flows. All three features are located on broad raised topography indicating that they may be underlain by a hot mantle plume, similar to that underlying the island of Hawaii. This

Figure 3-2. Mosaic of radar images of Ishtar Terra from the Venera 15 and 16 missions.

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Figure 3-3. Ushas, Innini, and Hathor Montes are volcanic structures along the western edge of this image taken at the Arecibo Radar Observatory. The plains to the east of the volcanoes contain belts of lineaments and an unusual grouping of circular features that may be of either volcanic or impact origin.

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group of peaks may be similar to Imdr Regio, centered at 43°S latitude and 210°E longitude, which will be imaged by Magellan in March 1991.

The first major impact crater that will be imaged is Meitner (see Figure 3-4), centered at 56°S latitude and 322°E longitude. Meitner, a multiringed basin about 85 kilometers (53 miles) across, may be similar to large multiringed basins on other planetary bodies, such as Orientale Basin on the Moon. It is believed that many of these basins on other planets have been the cause of volcanism. Has this been the case on Venus? Geologists also wonder about the effect of the hot Venus environment on impact basins. It is believed that Meitner may be relatively shallow because, under the influence of this heat, the crust "flowed away" with time. The plains to the east of Meitner contain complex belts of lineaments (also shown in Figure 3-4). Magellan data will be studied to determine whether these lineaments are ridges or grooves.

Again in the north, Magellan will be back covering Ishtar Terra, moving over the high Maxwell Montes region (see Figure 3-5). Near the high peak of Maxwell lies a 70-kilometer- (43-mile-) diameter circular depression called Cleopatra. The origin of Cleopatra is another subject of friendly debate. Some scientists argue that the crater was formed by a collapse that followed a giant volcanic eruption, while others believe that it is the result of a meteorite impact. Volcanism is evident, but it may have been triggered by an impact.

Fortuna Tessera (also shown in Figure 3-5) lies to the east of Maxwell Montes; it is a jumbled region of differing types of tesserae terrain. One theory of its origin suggests that different pieces of tesserae terrain have been pushed together to form this complex region, sort of like bumper cars slammed up against Maxwell Montes.

To the south of Fortuna Tessera in Bereghinya Planitia, Magellan will image arachnoids (see Figure 3-6), another class of features first identified in the Venera 15 and 16 data. We hope to gain an understanding of why arachnoids formed, what caused the odd weblike lineaments surrounding the structures, and why the features tend to form in clusters.

Moving south of Bereghinya Planitia, we come to Sif Mons, a peak in Eisila Regio (see Figure 3-7). Its dark central caldera, which may contain

Figure 3-4. Meitner crater is located near the upper left corner of this Arecibo Radar Observatory image. The large double-ring structure south of Meitner may be an impact crater or a corona. The widely spaced ridges in the plains east of Meitner may have formed from material pushed together or pulled apart. Image resolution is 2 to 3 kilometers (1 to 2 miles).

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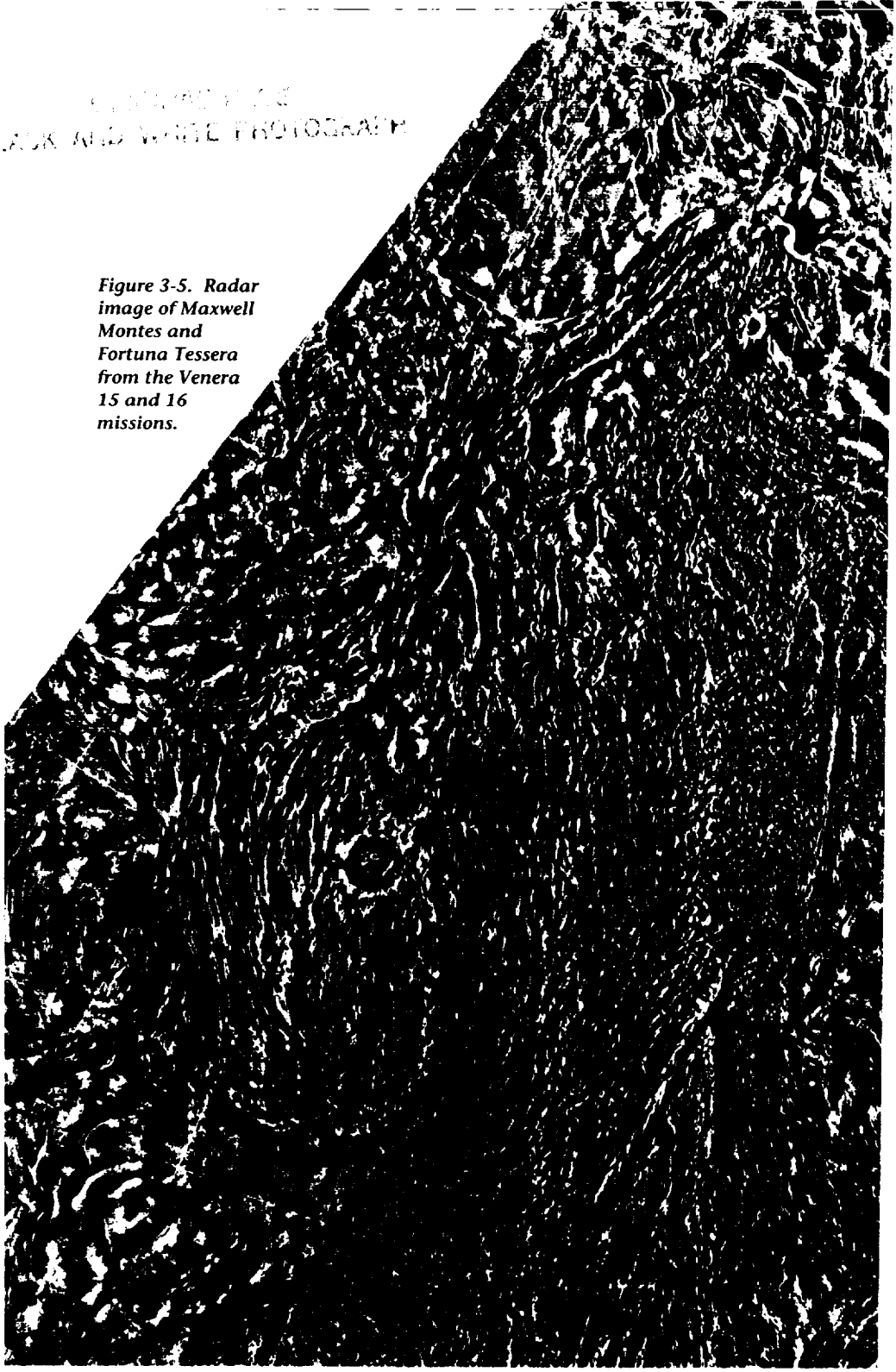

Figure 3-5. Radar image of Maxwell Montes and Fortuna Tessera from the Venera 15 and 16 missions.

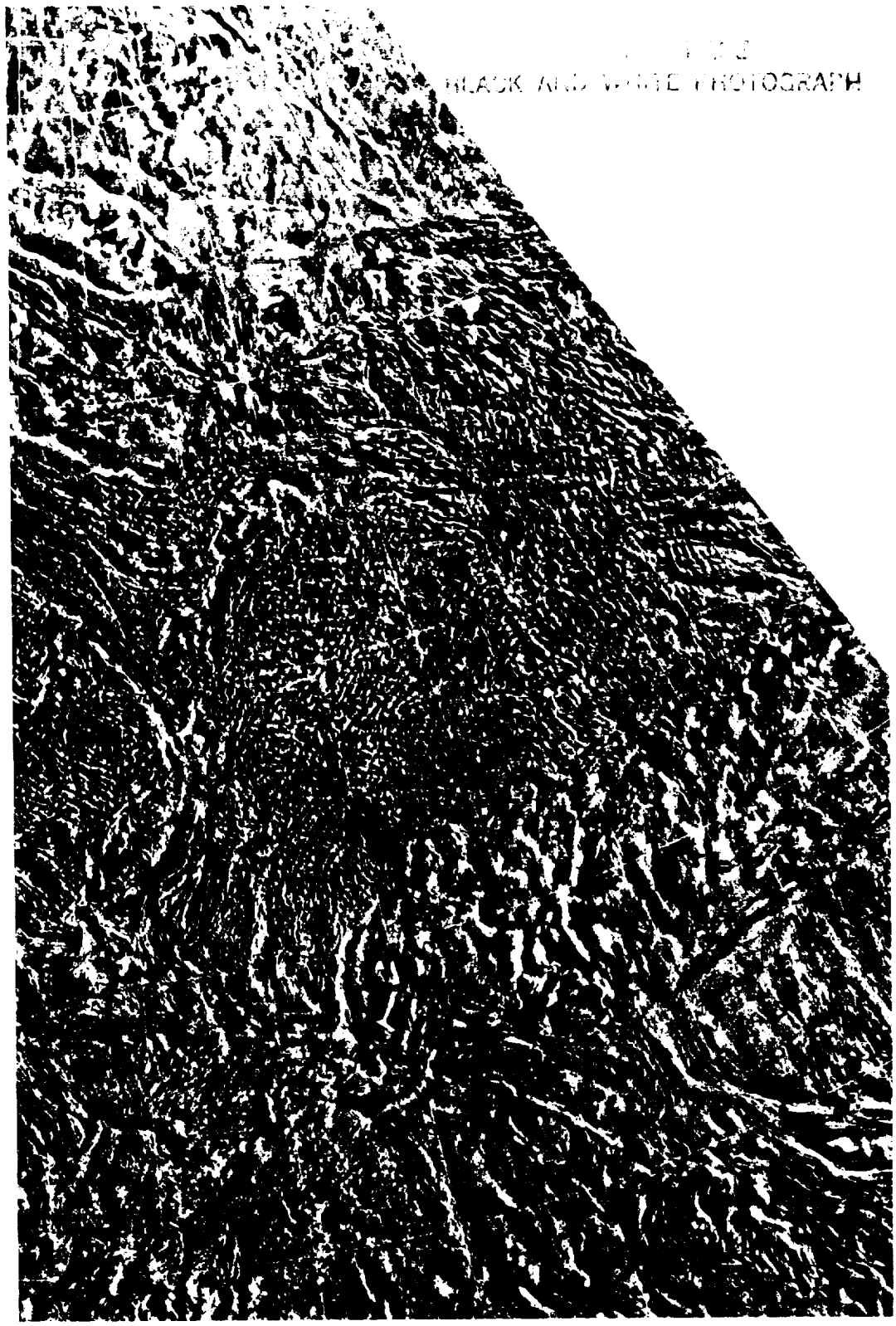
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Figure 3-6. Several arachnoid features are shown in this image from the Venera 15 and 16 missions. The circular structures measure about 100 kilometers (62 miles) across.

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Figure 3-7. This dramatic image of Sif Mons was obtained in 1988 at the Arecibo Radar Observatory. Image resolution is approximately 1 to 3 kilometers (0.6 to 2 miles).

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pools of lava, is surrounded by extensive flow features that seem to cascade down its flanks. Is this feature now active? If the Magellan Project is extended for additional 243-day mapping cycles, scientists could compare images of volcanic features, such as Sif, to detect current volcanic activity.

Traveling again into the southern hemisphere, we come across the highland region of Alpha Regio (see Figure 3-8). Previous radar images indicate that this is a region of tesserae. Tesserae tend to occur in rather polygonally shaped plateau regions, as well as in small islandlike regions in the plains. Do tesserae underlie all of the plains? Some geologists believe regions of tesserae have formed as the result of compressional forces, while others believe they were created at a spreading center and moved laterally out into the plains. Alpha Regio is similar in size and appearance to Tellus Tessera, centered at 35°N latitude and 82°E longitude, a region that will be imaged in early December 1990.

The topography south of Alpha Regio, called Lada Terra, seems to be a relatively high region that may be similar to Ishtar Terra. Farther south still lies the mysterious south polar region, an area that has never been imaged. Although Magellan's coverage during the first mapping cycle will not extend all the way to the south pole, it will reach much farther than that of any previous spacecraft, allowing us to see if Lada also contains mountain belts and regions of tesserae. (Magellan's ability to map the south pole during additional mapping cycles is discussed in Chapter 11.)

Returning north again, scientists will begin receiving images of Laima Tessera (see Figure 3-9) located at 50°N latitude and 40°E longitude. Laima differs from other regions of tesserae in that it has a distinct set of ridges intersected at right angles by long linear troughs. The morphology of this region is similar to that of the Earth's ocean floor, leading some scientists to postulate that Laima formed at a spreading center.

South of Laima is a small highland region called Bell Regio, which has a high volcanic peak named Tepev Mons (see Figure 3-10). Bell and Tepev will be imaged by Magellan in mid-November 1990. Bell is also thought to be underlain by a hot mantle plume. On Earth, most of the heat generated inside the planet by the decay of radioactive elements is

Figure 3-8. Image of Alpha Regio from the Arecibo Radar Observatory.

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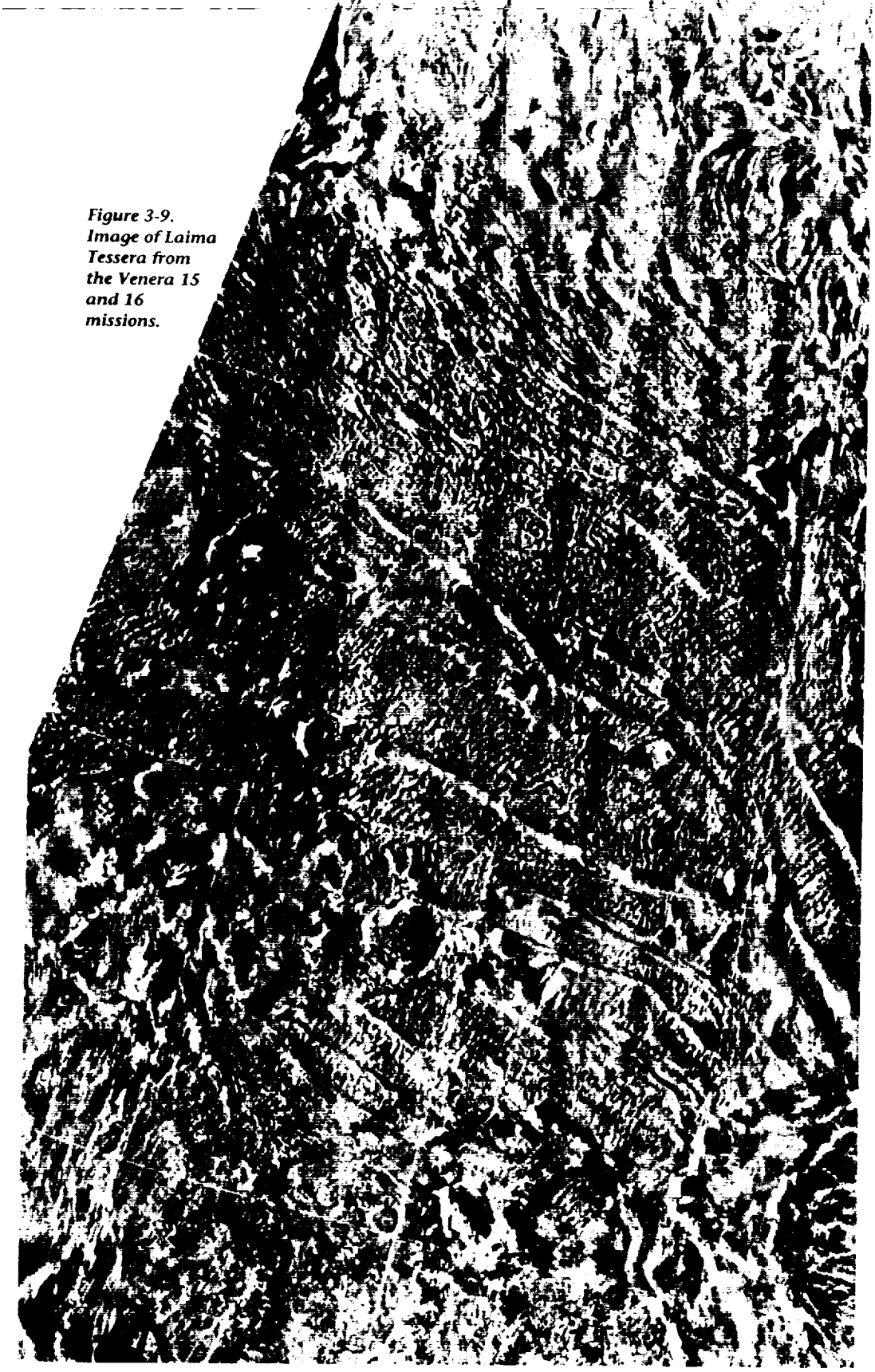

Figure 3-9. Image of Laima Tessera from the Venera 15 and 16 missions.

lost through the process of plate tectonics. On Venus, the internal heat may be creating many mantle plumes that form highland regions and volcanoes. High-resolution gravity data, which would be obtained during extended mission cycles, would help scientists solve this puzzle.

Also in mid-November 1990, Magellan will image what is probably the most actively debated region on Venus: Aphrodite Terra. Approximately the size of Africa, Aphrodite straddles the equator, is over 10,000 kilometers (6,214 miles) long, and is made up of four smaller highlands: Ovda, Thetis, Atla, and Ulfrun Regiones. Some geologists believe that Aphrodite is a spreading center, a linear zone where new crust is created and spread out laterally to the north and south, similar to the midocean ridge spreading centers on Earth (see Figure 3-11). Others believe that Aphrodite is underlain by mantle plumes with little or no crustal spreading.

The first areas of Aphrodite Terra that Magellan will cover are Ovda and Thetis Regiones, which are high plateaus cut by a central trough. Scientists will look for evidence that material has moved north or south away from this trough, similar to the way Iceland is being split by the Mid-Atlantic Ridge. If Thetis and Ovda are sites of new-crust production, the age of the surface should increase away from their central axes. In other words, Aphrodite would be the youngest region and Ishtar Terra (to the north) and Lada Terra (to the south) would be the oldest. Is there evidence of volcanism and transform faulting in this region? Can we identify anything like the plate boundaries we see on Earth?

South of Aphrodite is a lowland plains region called Aino Planitia. These plains are too far east to be imaged by Earth-based radar (because Venus always shows the same face toward Earth when it is near enough for the best study) and are south of the Venera spacecraft radar coverage. Thus, little is known about them. Are they ancient terrain characterized by many impact craters, or are they like the relatively young volcanic plains to the north? Airborne radar observations of the Sahara Desert on Earth penetrated through the top thin layers of sand and detected evidence of previous wetter climates (see Figure 3-12). Will the Magellan images show the present surface of the Venusian plains, or will we be looking through the top dry layers of regolith to an older

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Figure 3-10. The Venera 15 and 16 spacecraft imaged Bell Regio at the very southern end of their mapping coverage. Tepev Mons is at the center of the image. This region is interpreted to be the caldera of the volcano. The prominent black areas are gaps in the data.

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Figure 3-11. The Mid-Atlantic Ridge near Iceland. It is believed that Iceland was formed by a mantle plume beneath the spreading center. Magellan data may show that Aphrodite Terra is similar to the Mid-Atlantic Ridge.

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(a)

(b)

Figure 3-12. These images are of a 50- by 100-kilometer (31- by 62-mile) area along the Egyptian-Sudanese border. (a) Taken by the Landsat satellite's multispectral scanner band 6, this image shows a landscape dominated by eolian processes. The Selima sand sheet blankets the underlying material to a few meters in thickness. Streaks in the image represent sand dunes. (b) In contrast, this image from the Shuttle Imaging Radar-A experiment reveals a subsurface landscape carved by fluvial processes. The confluence of two large river channels is evident in the center of the image. The sand dunes cannot be seen.

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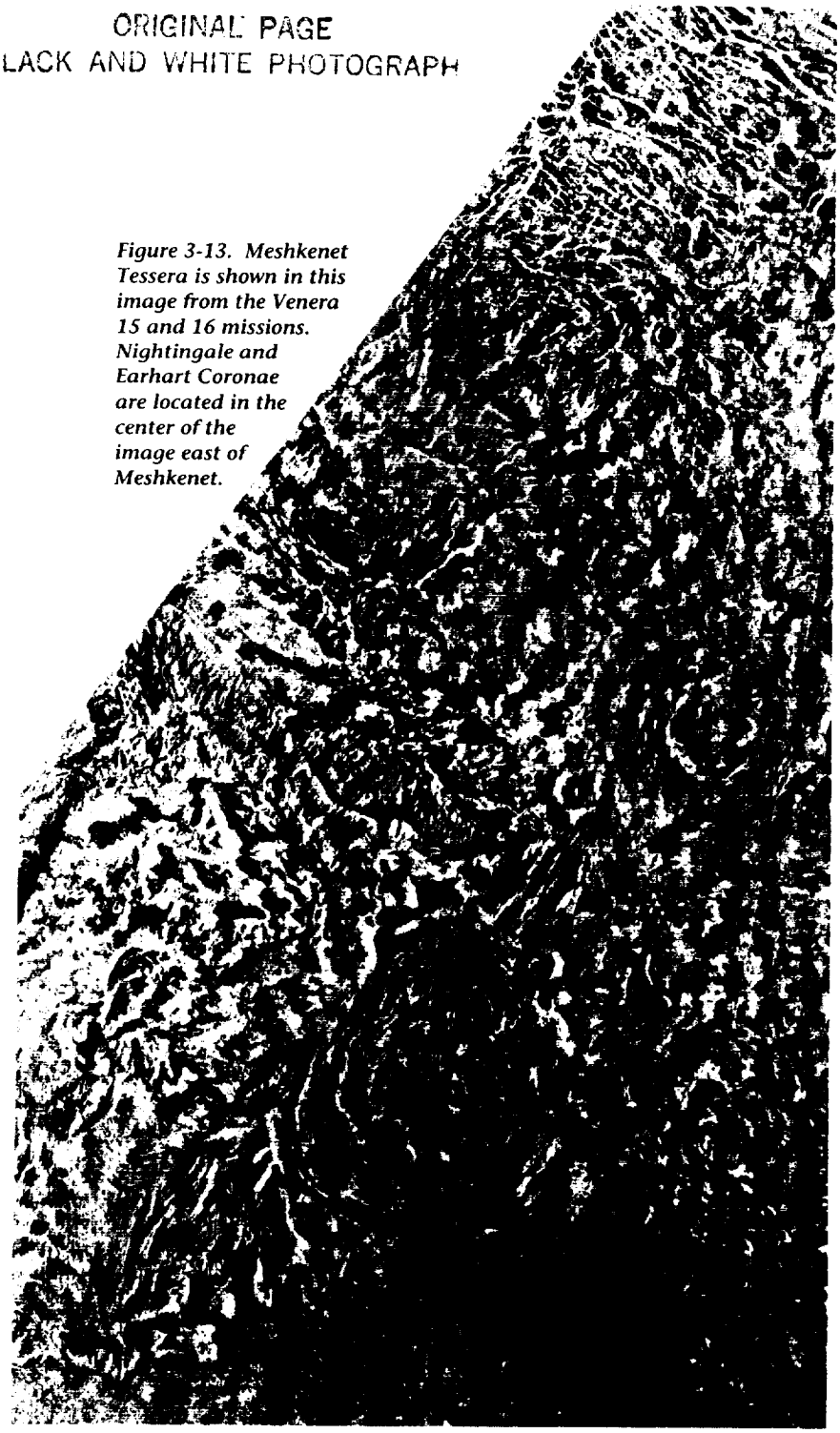

Figure 3-13. Meshkenet Tessera is shown in this image from the Venera 15 and 16 missions. Nightingale and Earhart Coronae are located in the center of the image east of Meshkenet.

subsurface layer? If there is evidence that water existed in Venus' past, we can determine when the greenhouse effect turned the planet into a place where no human can survive.

Heading north again, we see to the east of Fortuna Tessera a fragmented region of tesserae called Meshkenet Tessera (see Figure 3-13). This terrain appears to be flooded by volcanism from the surrounding plains, and thus seems to be relatively old. To the east of Meshkenet lie several large circular structures called coronae. Nightingale Corona, 560 kilometers (348 miles) in diameter, is surrounded by a ring of ridges over 1.5 kilometers (0.9 mile) high. Coronae are believed to form over hot mantle plumes that rise from the interior of the planet. Coronae range in size from 170 to 1,000 kilometers (106 to 621 miles), with most of the features lying in clusters to the west and east of Ishtar Terra.

To the south of Thetis Regio in Aphrodite lies Artemis (see Figure 3-14), one of the most enigmatic features on Venus. Magellan will begin mapping Artemis in late November 1990. Artemis is a large circular feature about 2,600 kilometers (1,616 miles) in diameter, with relatively raised topography surrounded by a deep narrow trough. Scientists wonder if this is the largest corona on Venus, or whether this region was similar to a high plateau, like Thetis, which has relaxed or flowed away with time.

Atalanta Planitia, centered at 64°N latitude and 163°E longitude, is a basin that extends for 1,500 kilometers (932 miles). Data from the Pioneer Venus spacecraft indicate that several areas within Atalanta contain rocks with unusual and/or unknown composition. There may be different erosional conditions or volcanic compositions that would produce these rocks; Magellan may detect sand dunes and wind streaks that result from eolian processes.

South of Atalanta is the central region of Aphrodite, which contains several deep troughs. Two of these troughs are called Dali and Diana Chasmata, and they contain some of the lowest elevations on Venus. Large troughs like these are thought to be rifts—areas where the crust or upper layer of the planet are pulled apart by extensional forces. The Soviet Vega 1 and 2 spacecraft landed on the southern and northern

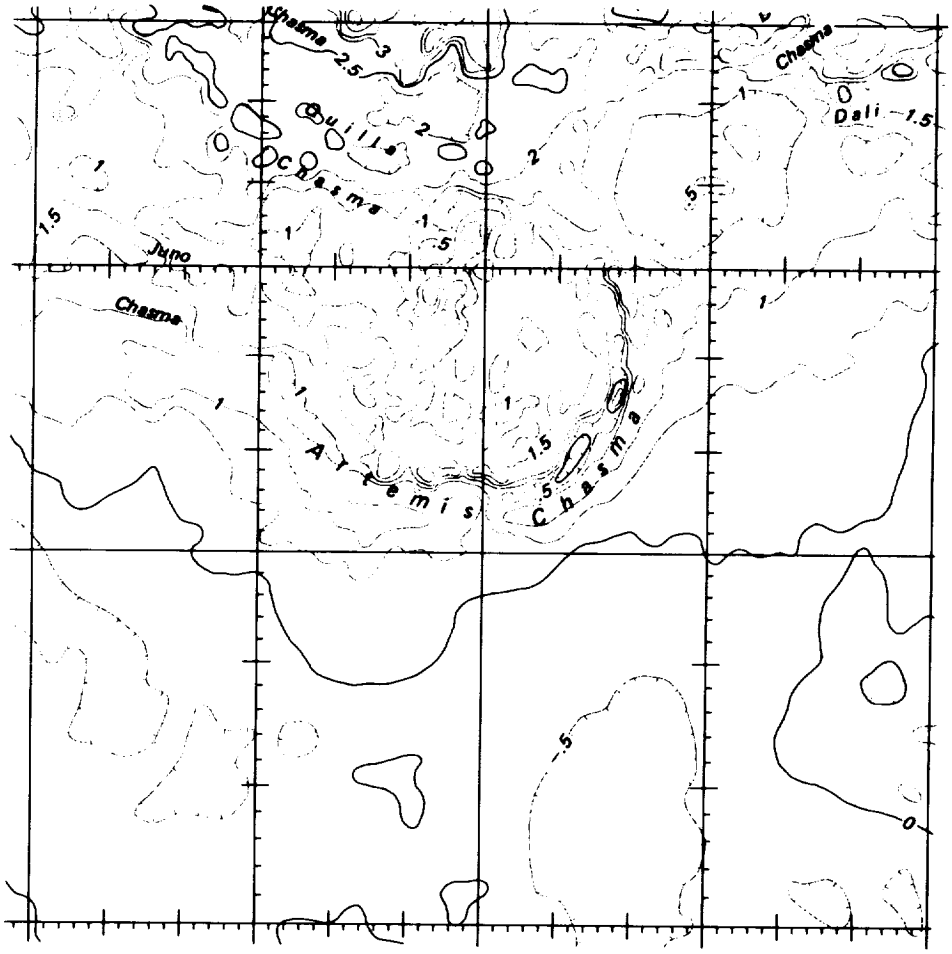

Figure 3-14. Topography of Artemis Chasma obtained by the Pioneer Venus spacecraft.

flanks of this region of Aphrodite and measured rock compositions similar to those of igneous rocks on Earth.

East of Atalanta Planitia lies Vinmara Planitia (see Figure 3-15), which will be imaged by Magellan in February and March 1991. This is a low-lying plains region with intertwining belts of ridges that extend for thousands of kilometers. There is much debate over whether these ridges are formed by extension—material being pulled apart—or by compression—material being pushed together. Scientists will search the Magellan images for features that will disclose the origin of these ridge belts, and perhaps why they occur as a fan-shaped group in this region.

South of Vinmara, on the eastern end of Aphrodite, are two elongate highlands called Atla and Ulfrun Regiones. Atla and Ulfrun contain many high peaks thought to be volcanic in origin, but which have never been imaged at high resolution. Will they be characterized by lava flows, like Sif Mons in Eisila Regio, or are they long-dormant, eroded volcanoes?

Back up north again, Magellan will image several large coronae and volcanoes in March 1991. Bachue Corona (see Figure 3-16) is located in Metis Regio and is raised over 2 kilometers (1 mile) above the surrounding region. Bachue may be a corona in the process of forming, since it is only partially surrounded by a ring of ridges. Mokosha Mons, a little to the south of Bachue, is a 350-kilometer- (217-mile-) wide volcanic structure (see Figure 3-17). It has a complex central caldera surrounded by many lava flows. Mokosha probably formed over a long period of time, with multiple phases of eruptions, similar to large complex volcanoes on Earth.

South of Mokosha and heading east out of Aphrodite are several long, linear troughs named Hecate and Parga Chasmata. These troughs have raised rims and extend for thousands of kilometers, a configuration similar to the troughs in central Aphrodite. The troughs may be comparable to the long linear rifts that lie along the midocean ridges on Earth. Hecate Chasma leads into Asteria Regio, a small highland region of unknown geology that will first be imaged in early April 1991.

Southeast of Pargo Chasma are the strange circular features of Themis Regio (see Figure 3-18). Themis is composed of over seven multiple-ring features, with the diameter of the outer ring measuring over 300 kilometers (186 miles). Are these large impact craters, coronae, or something completely different? Coronae in the northern hemisphere do not tend to form in chains as these features do. Perhaps the Themis features are formed by large bodies of molten rock rising along a zone of extension.

Finally, at the end of the 243-day mapping cycle, Magellan will be situated at 276°E longitude, over the region where it first came into orbit. Here it will map Beta and Phoebe Regiones, two highland regions in the equatorial zone that are characterized by a north–south trough, Devana

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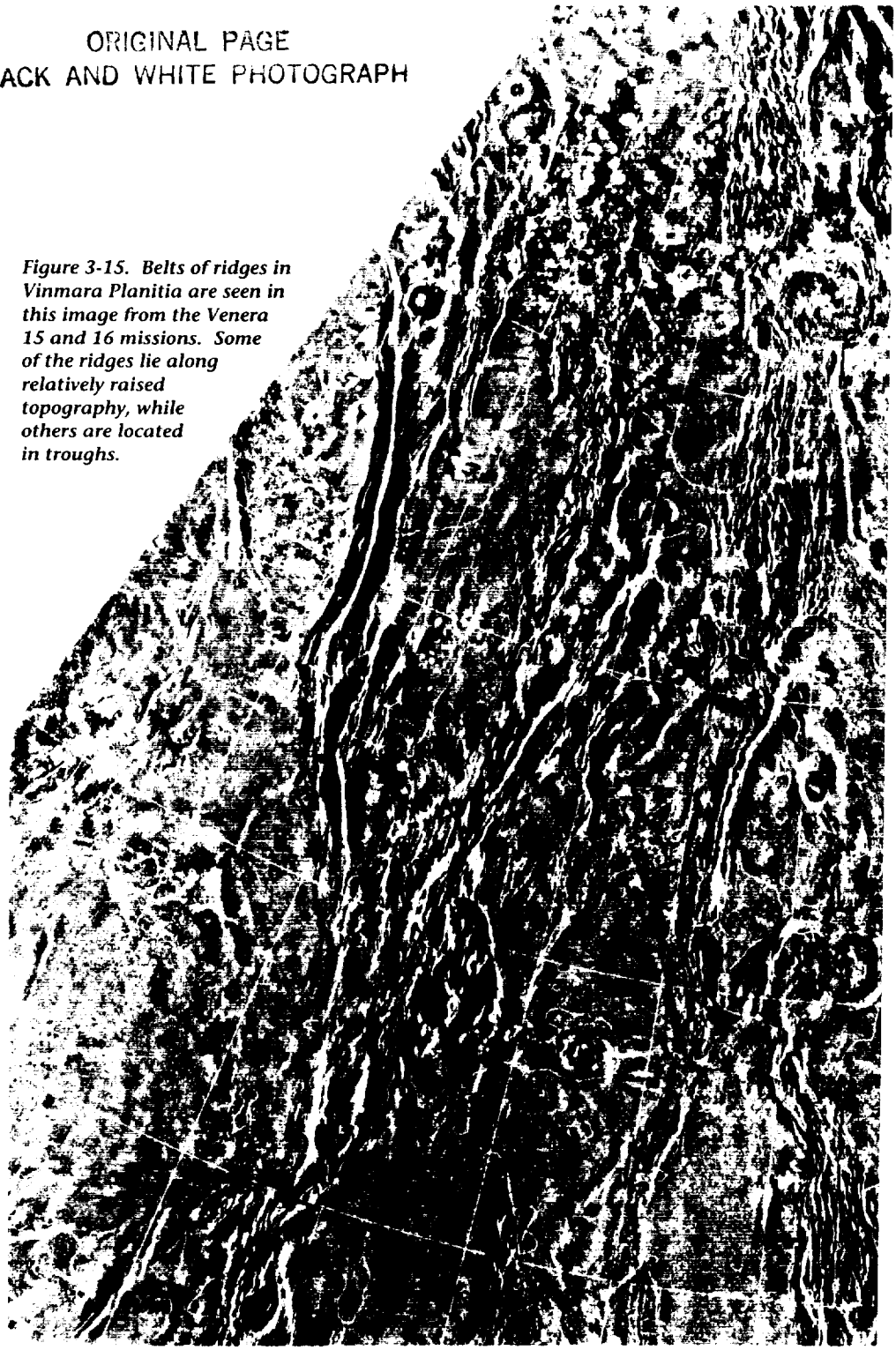

Figure 3-15. Belts of ridges in Vinmara Planitia are seen in this image from the Venera 15 and 16 missions. Some of the ridges lie along relatively raised topography, while others are located in troughs.

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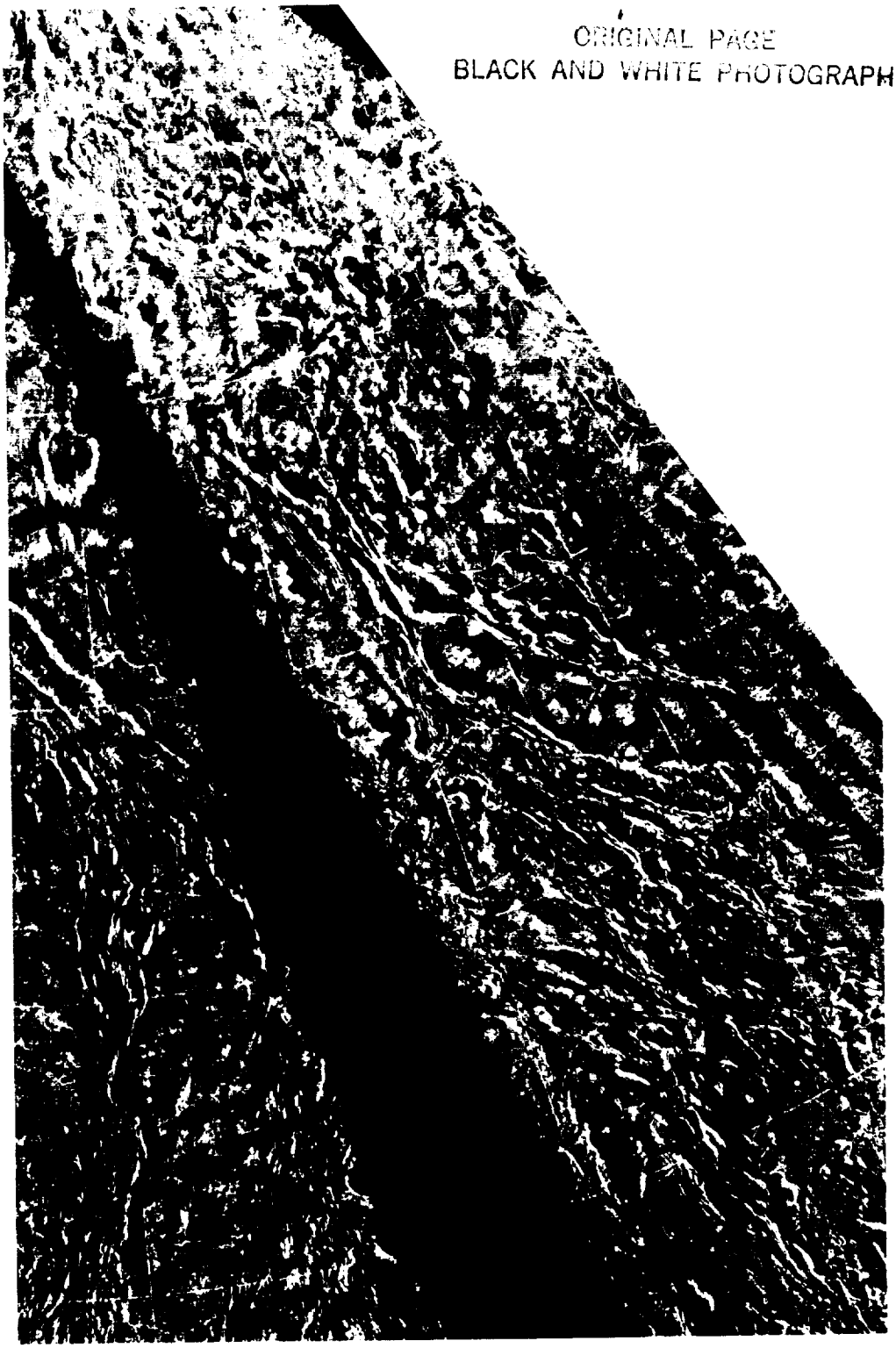

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Figure 3-16. Bachue Corona, which has a diameter of about 650 kilometers (404 miles), was imaged by the Venera 15 and 16 spacecraft.

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Figure 3-17. Mokosha Mons is in the center of this image from the Venera 15 and 16 missions.

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Figure 3-18. This image of Themis Regio, a highland region rising about 2.5 kilometers (1.6 miles) above the surrounding plains, was taken at the Arecibo Radar Observatory.

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Figure 3-19. The high topography of Beta Regio is cut by Devana Chasma, a trough that contains radar-bright lineaments interpreted to be faults. Two large volcanoes, Rhea and Theia Montes, can be seen at the northern and southern ends, respectively, of Beta Regio. This image was taken at the Arecibo Radar Observatory.

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Chasma (see Figure 3-19). Beta is similar in size and general morphology to the East African Rift Zone on Earth, a region where the crust of the planet is being pulled apart. Scientists will use Magellan data to determine how much extension has taken place. Some scientists also believe that Beta is the most likely place on the planet to detect active volcanoes.

Over the course of one Venus rotation (243 Earth days), the Magellan spacecraft will map most of the surface with detail that exceeds that of the best previous radar images. The resultant maps will reveal the traces (if they exist) of many fundamental planetary forces: volcanism, wind, water, and meteorite impacts—in short, all the processes that determine a planet's history and shape its face. By giving us this new information, Magellan will not only tell us more about Venus, our nearest planetary neighbor, but perhaps will provide the insight we need to fully understand the forces that continue to shape our own Earth.

The ship, a fragment detached from the earth,
went on lonely and swift like a small planet.

— Joseph Conrad

Chapter 4
The Magellan Spacecraft

The design of the Magellan spacecraft was driven by the need for a low-cost, high-performance vehicle. The spacecraft for the earlier VOIR mission was to have been custom-designed and built, but the Magellan Project saved many of those costs by taking advantage of an inventory of mission-proven technologies and spare components (see Table 4-1).

Magellan's simpler design also meant that some components would perform more complex tasks. For example, instead of using separate antennas for mapping and telemetry, the craft's primary antenna will perform both of these functions.

The team that designed Magellan worked within the stringent budgetary and performance requirements and produced a spacecraft that complied with the Project's fiscal reality and one that has our highest confidence in its ability to carry out the objectives of the Magellan mission.

Overall Physical Appearance

The Magellan spacecraft (see Figure 4-1) that was loaded in the cargo bay of the Space Shuttle Atlantis weighed 3,453 kilograms (7,612 pounds) and consisted of

(1) Antennas (high-, medium-, and low-gain, plus altimeter).

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Table 4-1. Equipment from Other Spacecraft

Component	Source
Medium-gain antenna	Mariner Mars 1971
High- and low-gain antennas	Voyager
Equipment bus	Voyager
Star-scanner design	Inertial Upper Stage
Radio-frequency traveling-wave tube assemblies	Ulysses
Attitude-control computer	Galileo
Command and data subsystem	Galileo
Thruster rockets (small)	Voyager
Electric-power distribution unit	Galileo
Power control unit	P-80 satellite
Pyrotechnic control	Galileo
Solid-rocket motor design	Space-shuttle payload assist module (PAM)
Propellant-tank design	Space-shuttle auxiliary power unit

(2) Forward equipment module.

(3) Equipment bus.

(4) Solar panels.

(5) Propulsion module.

(6) Solid-rocket orbit-insertion motor.

(7) Inertial-Upper-Stage (IUS) adapter structure.

The parabolic, dish-shaped, high-gain antenna (HGA) dominates the top of the stack. The dish is made of strong, lightweight, graphite-epoxy sheets mounted to an aluminum honeycomb for rigidity. This antenna, further described in the telecommunications section of this chapter, functions as the primary antenna for radar operations, transmission of radar data, receipt of radio signals from Earth, and transmission of engineering health data to Earth.

The medium-gain antenna (MGA) is the cone-shaped structure mounted to the top side of the equipment bus. The low-gain antenna (LGA) is mounted on a platform held by struts above the HGA. Both of these antennas augment the HGA and are useful when the HGA cannot be pointed directly at Earth.

The altimeter antenna (ALTA) is mounted on the side of the forward equipment module (FEM), extending forward from beneath the HGA dish. It is used exclusively for radar altimetry. During the mapping part of each Venus orbit, the ALTA is pointed vertically down at the planet to provide one-dimensional readings of the heights of surface features. The 1.5-meter- (5-foot-) long aluminum structure has an aperture of 0.6 × 0.3 meter (2 × 1 feet) and weighs 6.8 kilograms (15 pounds).

The FEM houses the radar electronics, radio telecommunications equipment, certain attitude-control equipment, batteries, and the power-conditioning unit (see Figure 4-2). The boxlike housing measures 1.7 × 1.0 × 1.3 meters (5.3 × 3.3 × 4.3 feet) and is made of aluminum panels on a framework of square aluminum tubing that has been chemically milled for weight reduction. Two sides of the FEM have louvers for thermal conditioning. Mirror-surfaced covers shield the louvers from the intense sunlight at Venus.

Immediately below the FEM is the 10-sided equipment bus, built originally as a spare for the Voyager Project. The bus is a bolted aluminum structure with aluminum cover plates. It measures 42.4 centimeters (16.7 inches) high and approximately 2.0 meters (6.6 feet) across. Each of its 10 compartments is a 42- × 47- × 18-centimeter (16.5- × 18.5- × 7-inch) enclosure for electronics. An opening in the middle of the ring of compartments holds the hydrazine fuel tank for the liquid-propulsion system.

The bus compartments contain the flight computers, the input/output interface between the computers and Magellan subsystems, tape recorders, solar-array controls, solid-state bulk memory, and pyrotechnic control electronics.

The two square solar panels, shown in Figure 4-3, measure 2.5 meters (8.2 feet) on a side and together can supply 1,200 watts of power. With the arrays deployed, Magellan spans 10 meters (32.8 feet) from tip to tip of the panels. The light-colored lines visible on them are solar reflectors that keep the temperature of the arrays below 115 degrees centigrade (239 degrees Fahrenheit), even in full sunlight at Venus. Approximately 35 percent of the front surface is reflective mirrors, and the back surface is 100 percent mirrors.

(a)

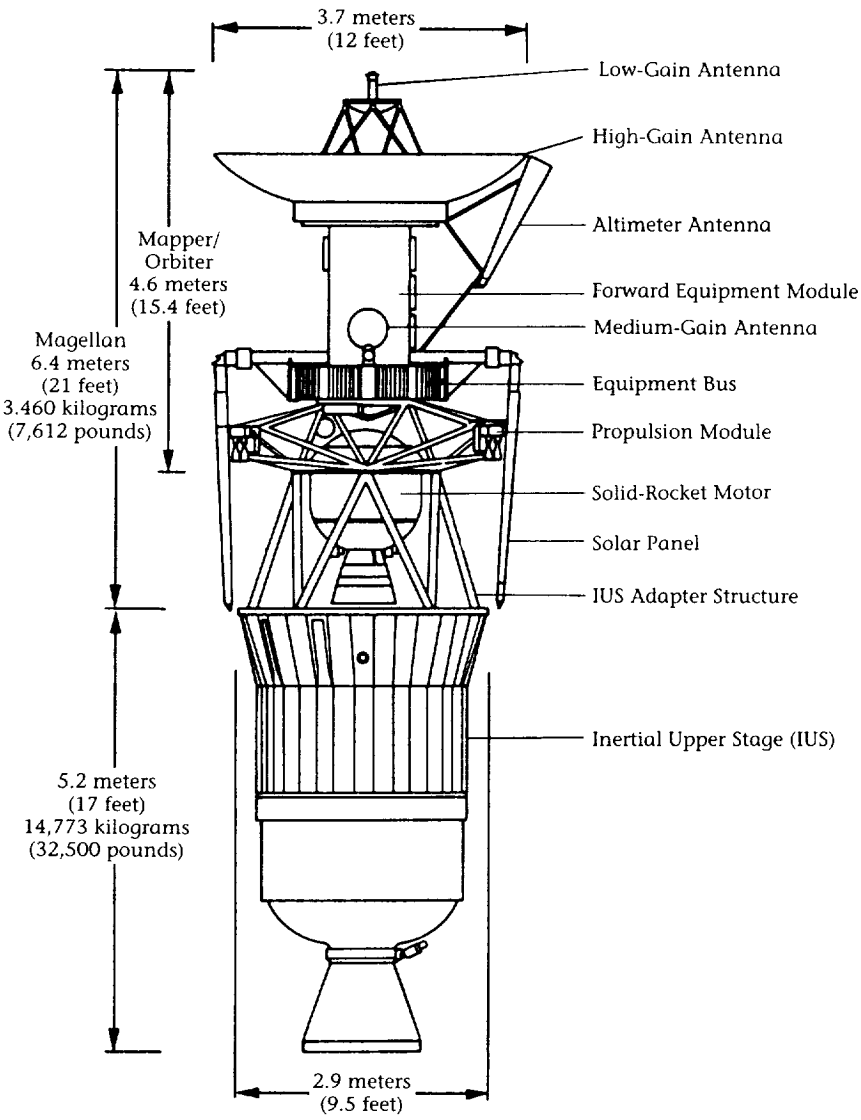
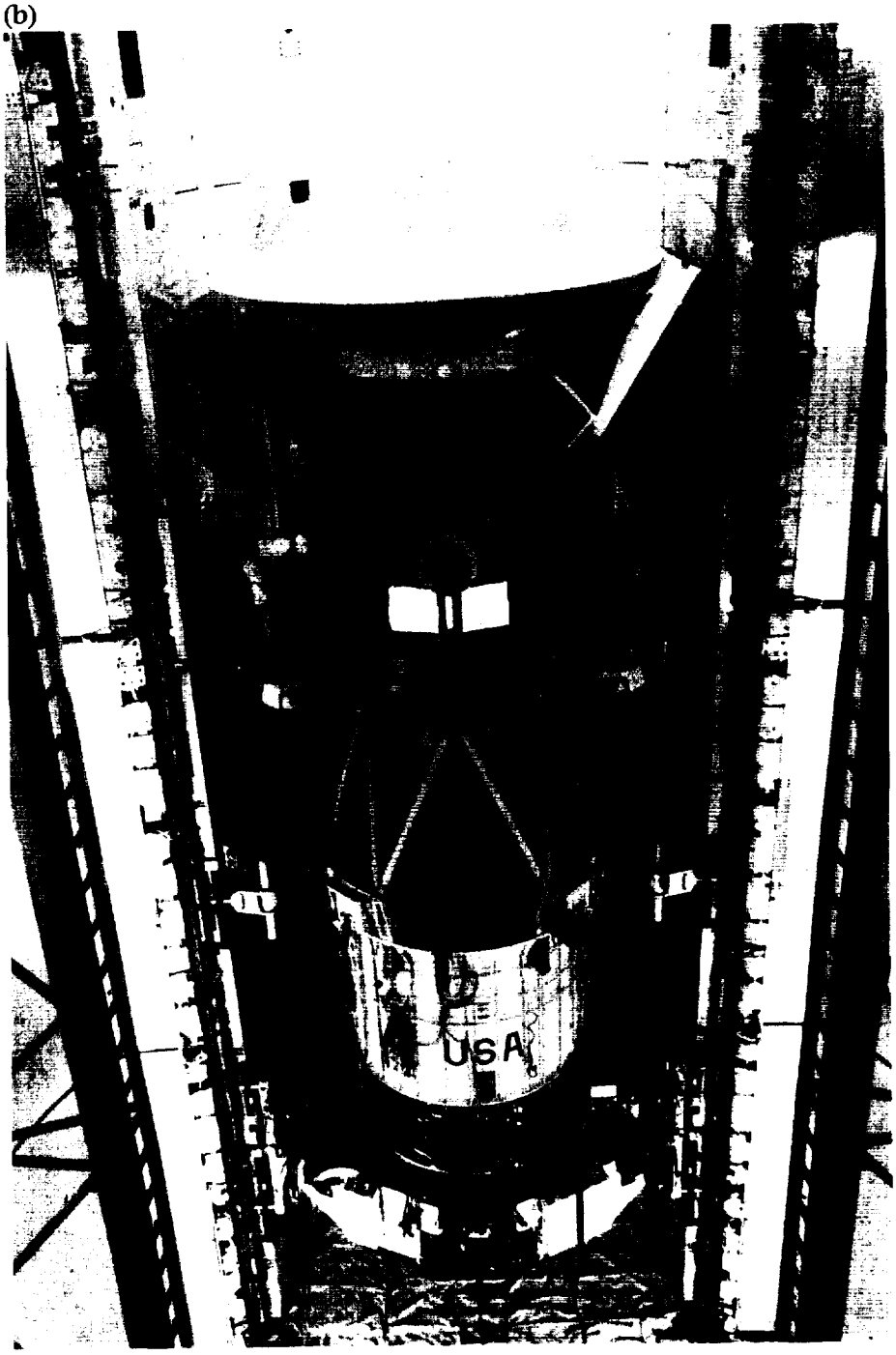


Figure 4-1. The Magellan spacecraft: (a) The Magellan/IUS combination; (b) Magellan and the IUS loaded in the cargo bay of the Space Shuttle Atlantis.

(b)



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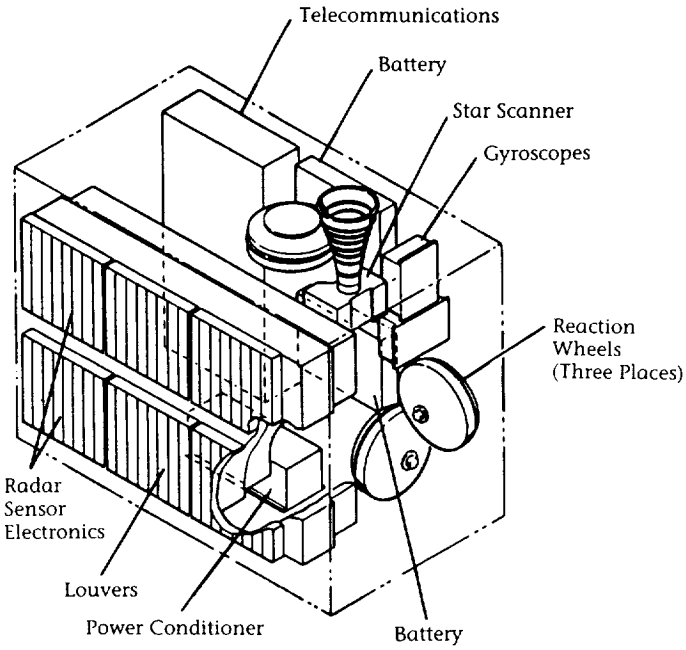

Figure 4-2. Forward equipment module.

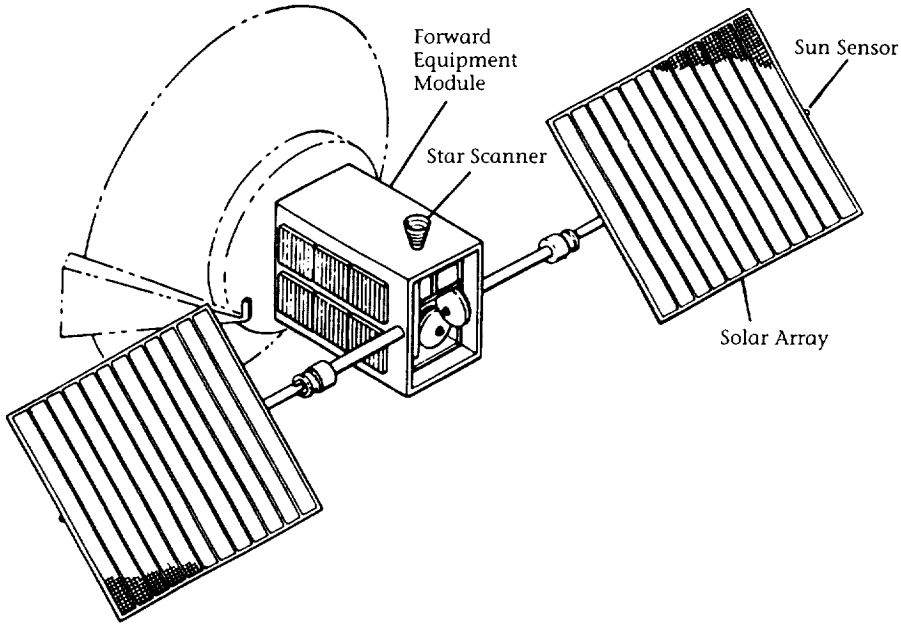

Figure 4-3. Forward equipment module and solar arrays.

The panels are hinged for stowage in the shuttle and were deployed while Magellan was in Earth orbit. During interplanetary cruise and in orbit around Venus, they rotate to follow the Sun. Solar sensors on the panel tips and a control package in the equipment bus maintain the panels' sunward orientation. The honeycomb aluminum backing structure, arms, and oversized joints are designed to enable the panels to withstand the force produced by the rocket burn that will insert Magellan into Venus orbit.

The propulsion equipment shown in Figure 4-4 includes a 24-thruster liquid-propulsion module and the solid-rocket motor (SRM) used for orbit insertion. The propulsion-module structure provides precisely aligned attachment of the SRM, as well as the liquid-propellant thrusters and associated plumbing, which are needed for trajectory/orbit corrections, attitude control during orbit insertion, and other functions.

The propulsion module also provides the attachment points for the IUS adapter structure. Both structures are made of graphite-epoxy trusses with sculptured titanium end fittings. Explosive bolts released the adapter, along with the IUS, after IUS burnout.

Spacecraft Equipment

The spacecraft equipment can be grouped into several functional subsets: the radar sensor and altimeter antenna; telecommunications, including radio equipment and antennas (except the altimeter antenna); spacecraft attitude control and solar-panel articulation control; electrical power; propulsion and pyrotechnic control; thermal control; and structure and mechanisms. The radar equipment and functions are described in Chapter 5. The remaining subsets, which comprise the engineering subsystems, are described below.

Telecommunications

Acquiring detailed knowledge of Venus' surface depends as much on Magellan's ability to send large amounts of data to Earth as it does on the radar equipment itself. Most of the communications components for sending, receiving, and decoding radio signals are located in the FEM. These components include a redundant set of receivers, command

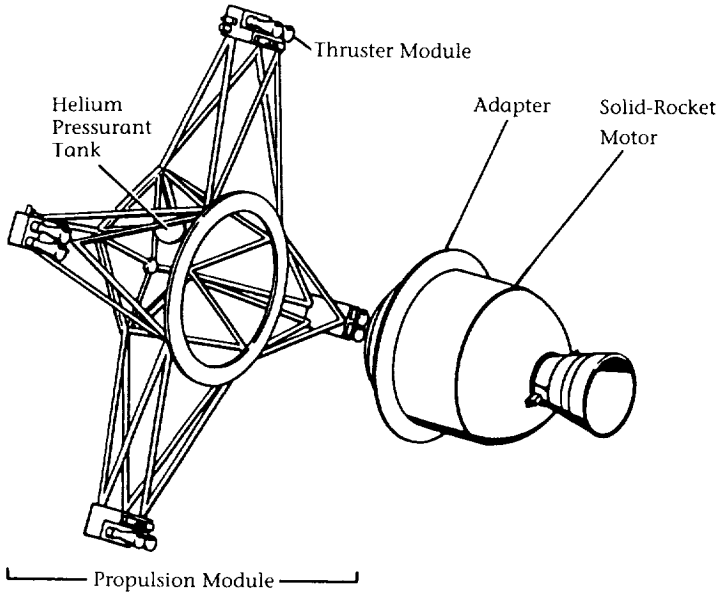

Figure 4-4. Elements of the propulsion module.

detectors, transmitters, data encoders, data modulators, exciters, control units, and switches used to interconnect them in various combinations with each other and with the externally mounted communication antennas. A receiver, command detector, exciter, and low-power amplifier are packaged together into an assembly called a NASA-standard transponder, of which there are two on Magellan. In addition to the low-power amplifiers in the transponders, there are two high-power amplifiers called traveling-wave tubes. The NASA-standard transponder and traveling-wave tube assemblies enable Magellan to transmit at a peak rate of 268.8 kilobits per second. In comparison, the Viking Orbiter in 1976 transmitted its detailed images of Mars at 16 kilobits per second.

Magellan uses two different transmitters that operate on the S and X frequency bands for communications with Earth. S-band, with a frequency 2,000 times higher than the AM radio broadcast band, is used for transmitting engineering data to Earth and for most command transmissions from Earth to the spacecraft. The high S-band frequency enables the HGA to concentrate the spacecraft's low-power (5-watt) engineering signals so that they can be detected on Earth from distances up to 257 million kilometers (160 million miles). X-band transmission,

at a frequency rate almost four times greater than that of S-band, enables the HGA to transmit an even more concentrated signal to Earth. The use of X-band and a higher signal power (20 watts) enables the high data rates used for transmitting radar data to Earth.

From Venus orbit, this system will send engineering data about the spacecraft's condition to Earth at 1.2 kilobits per second through the HGA via S-band and simultaneously transmit the radar data at 268.8 kilobits per second via X-band. Backup data rates of 40 bits per second for engineering telemetry and 115.2 kilobits per second for radar data are available for certain circumstances or emergencies.

Working with the radio transponder, modulators, and amplifiers to make up a complete telecommunications subsystem are the high-, medium-, and low-gain communication antennas.

The 3.7-meter- (12-foot-) diameter HGA is critical to all aspects of the mission. It transmits and receives the mapping radar pulses, collects radiant energy emitted by Venus (for the radiometry experiment), sends science and engineering data to Earth, and receives commands from Earth that direct spacecraft activities. The HGA has a total beamwidth of 2.2 degrees at S-band and 0.6 degree at X-band.

The MGA is used primarily for sending commands to and receiving engineering data from Magellan during the Venus orbit-insertion (VOI) maneuver and during portions of the 15-month cruise period. Because its 18-degree beamwidth provides telemetry capability without the precise pointing required by the narrow-beam HGA, the MGA is also used for emergency situations when spacecraft pointing may not be correct.

The LGA, mounted on the top of the HGA, is placed so that no part of the spacecraft can interfere with its broad beam. Its design allows commands to be received from any direction within 90 degrees of its central axis. This hemispherical coverage pattern greatly reduces the need to precisely point the spacecraft during an emergency. An example would be a solar flare that produces energetic particles strong enough to alter the computer program used by the attitude-control subsystem. This type of anomaly would be sensed by the spacecraft, recognized as having a potential effect on pointing the HGA, and cause

the spacecraft to begin corrective actions, including switching to the LGA for command reception from Earth. Thus, ground controllers would be able to augment the spacecraft's corrective actions, if required.

Attitude Control

Magellan is a three-axis-stabilized craft, but it is required to perform frequent changes of its orientation in space as it orbits Venus. Keeping track of its precise orientation at all times via gyroscopes, this maneuvering is performed with reaction wheels controlled by one of two ATAC-16 computers located in the equipment bus.

During each orbit of Venus, Magellan will rotate four times: away from the planet to aim the HGA earthward for data transmission, toward space to scan stars for precisely determining any spacecraft-orientation errors, again toward Earth to resume data transmission, and back toward the surface of Venus for mapping. Throughout each elliptical orbit's mapping pass, the spacecraft continuously maneuvers in small increments to adjust the pointing of the HGA as the distance to the surface of the planet changes.

Throughout the mapping phase of the mission, there are 1,852 orbits requiring 7,408 major attitude changes in 243 days. If these attitude changes were performed solely with rocket thrusters, there would be more than 14,800 thruster burns for each of the spacecraft's three control axes (one to start a maneuver, another to stop it, and periodic thruster burns to control the rate). Indeed, Magellan would need immense fuel tanks.

However, Magellan is miserly with the fuel in its single, small, propellant tank. The repetitive attitude changes are instead accomplished with reaction wheels that use the principle known as Newton's Third Law: for every action there is an equal and opposite reaction. An illustration of this is a child jumping from a wagon. If the wagon is initially at rest, and the child jumps out the back of the wagon, the wagon moves forward as the child moves backward.

When it is desired to turn Magellan in a particular direction, an electric motor inside the spacecraft is commanded to spin a reaction wheel (a rotatable mass approximately 36 centimeters [14 inches] in

diameter) in the opposite direction. By Newton's Third Law, the spacecraft turns in the intended direction while the reaction wheel spins in the opposite direction. The spacecraft turn is stopped by commanding the motor driving the reaction wheel to stop. Three reaction wheels, one for each possible axis of rotation, are located in the FEM.

In theory, this system could work on its own, without thrusters, forever. But the reaction wheels must also be used to oppose outside forces (i.e., solar pressure and Venus gravity) that cause Magellan to rotate. As a result of the accumulation of these disturbances, the reaction wheels steadily build up speed. Eventually, the wheels would reach their maximum speed, or saturate, and become useless in controlling the spacecraft. Therefore, thrusters are fired briefly twice a day to allow the reaction wheels to "desaturate," i.e., reduce their speed to near zero. Tachometers on the reaction wheels determine the amount of thruster firing needed to desaturate the momentum built up by the external forces.

The job of keeping track of the spacecraft's current orientation is accomplished with gyroscopes and a star scanner. The gyroscopes sense any rotational rate, which is then integrated by the attitude-control computers to determine the spacecraft's current orientation. When the spacecraft orientation is more than a preset amount (usually 0.01 degree) from what it should be, appropriate reaction wheels are commanded to speed up or slow down until the orientation is again within bounds.

Projecting from one side of the FEM is the barrel of the star scanner (see Figure 4-3). This highly accurate attitude-sensing device is used to periodically correct errors due to drift of the gyroscopes. Once a day during cruise and once an orbit during mapping, the spacecraft performs a star scan. This involves turning the spacecraft to a preset starting position, after which a single rotation is used to sweep the optical star scanner across two known reference stars that are 80 to 100 degrees apart. The stars' apparent positions are calculated by the attitude-control computer using the gyroscope inputs, and these positions are compared with the stars' true positions, which are contained in data previously stored in the computer. The difference represents how

much the gyroscope drift has affected the computer's knowledge of its own attitude since the last star scan. This error has typically been less than 0.1 degree per day during the cruise period. The computer autonomously updates its attitude, as well as its own drift-compensation model, based on the determined error.

Did you know . . .

After orbiting Venus for more than a dozen years, there will be sufficient onboard propellant only to desaturate the reaction wheels. There will not be enough propellant to prevent the orbit from decaying, which will result in Magellan eventually entering the atmosphere of Venus and burning up.

Rounding out the complement of attitude-control hardware are sun sensors and solar-array drive motors, which keep the solar panels pointed toward the Sun. The sun sensors are located on the outboard tips of the solar panels and feed information to the computer about the current position of the Sun. The computer responds by commanding the solar-array drive motors until the solar panels are as close to pointing at the Sun as possible. Because the panels can be rotated around only a single axis while the spacecraft can rotate about three axes, it is not always possible to point the panels directly at the Sun. However, most of the time the spacecraft attitude is programmed to keep the solar panels' rotational axis perpendicular to the sunline, which allows the panels to point exactly at the Sun.

Electrical Power

Magellan operates on 28 volts fed through a power-conditioning unit in the FEM. The power source is the solar arrays, a pair of nickel-cadmium batteries, or the solar arrays and batteries used simultaneously. Either battery could support the mission with only a moderate amount of data loss should the other fail.

The solar panels directly supply all power required by the spacecraft during cruise and the data-transmission periods during mapping opera-

tions in Venus orbit; this includes recharging the batteries. The batteries augment solar-panel power during mapping, when the radar is drawing maximum power. When Venus occults the Sun from the spacecraft, the batteries supply the entire spacecraft power load.

Command and Data Handling

The command and data subsystem (CDS) decodes, stores, and distributes commands received from Earth to control spacecraft activities. These include commands to the attitude-control subsystem that regulate the position of Magellan and its back-and-forth changes between data gathering and transmitting. Other commands control radar-operating parameters and sequence other spacecraft subsystems through their operational states, as required. Most commands for controlling the spacecraft are stored for later distribution. The CDS can execute commands immediately upon receipt, however, if that is required.

The CDS' second function is to gather the engineering and radar data, format it for readability on Earth, pass it to the telecommunications subsystem for immediate transmission in the case of engineering data, or pass it to a tape recorder for storage and later transmission in the case of radar data. Engineering data can also be stored on tape if there is no communication with Earth at the time the data are gathered.

Redundant tape recorders, called the Data Management Subsystem (DMS), each provide storage for 1.8 gigabits of data. During the orbital mapping phase, the DMS is used almost entirely for radar data, but some spacecraft engineering data are stored there also. In addition to tape storage, the CDS bulk memory is used to hold 5 kilobytes of sampled engineering data when real-time transmission of telemetry from Magellan is interrupted, for example, when the spacecraft is behind Venus. These sampled data are read out to Earth immediately after the data interruption is over.

Propulsion

The 24 multipurpose liquid-propellant (hydrazine) thrusters provide several functions: spacecraft attitude control, trajectory/orbit correction, and reaction-wheel desaturations. Positioned in the middle of the

10-sided equipment bus is the single propellant tank that, at launch, contained 132.5 kilograms (293 pounds) of monopropellant hydrazine. A helium tank is attached to the struts of the propulsion-module structure and will be used, if necessary, to offset a drop in the pressure of the hydrazine system, a drop that would reduce thruster output level. The helium pressurant will be used if Magellan's interplanetary trajectory requires a major corrective firing of the thrusters, which, in turn, would drop the system pressure.

At each of the four outboard tips of the propulsion structure is a group of six thrusters: two of 100-pound, one of 5-pound, and three of 0.2-pound thrust. The large 100-pound thrusters, aimed aft, are used for large midflight course corrections, large orbit-trimming corrections, and controlling the spacecraft while the SRM burns during VOI. The 5-pound thrusters, aligned perpendicularly to Magellan's centerline, keep the spacecraft from rolling during those same maneuvers.

For the duration of the interplanetary cruise and mapping phase, the tiny 0.2-pound thrusters provide thrusts to desaturate the reaction wheels; they can be used for attitude control, if required. Eight 0.2-pound thrusters point aft and four are positioned for roll control. The aft-facing thrusters are also used for small course corrections and orbit trims.

The SRM used for orbit insertion at Venus is the Star 48B, the same motor used to send commercial communications satellites into geosynchronous orbit around Earth. The "B" denotes a motor using a carbon-phenolic nozzle, rather than the newer carbon-carbon nozzle. The motor weighs 2,146 kilograms (4,731 pounds), of which 2,014 kilograms (4,440 pounds) is propellant.

The motor's thrust will reduce Magellan's speed for transfer from the spacecraft's interplanetary trajectory into an orbit around Venus. The motor is aligned with the spacecraft's center of gravity to within 0.25 centimeter (0.1 inch) to provide sufficient balance of mass during the SRM burn to allow the 100-pound thrusters to maintain stability and prevent the spacecraft from tumbling.

Pyrotechnic Control

Attached to the underside of one equipment bus compartment is a box containing the control electronics that arm, disarm, and fire detonators to activate various explosive bolts, pin-pullers, and other devices. These enable release of the solar panels from their stowed position after deployment from the shuttle, actuation of propulsion valves, ignition of the SRM, and separation of the spent SRM after orbit insertion.

Thermal Control

Magellan will be subjected to sunlight approximately twice as intense as that which reaches Earth, potentially for several years. On the other hand, shaded exterior spacecraft temperatures can plunge to –204 degrees centigrade (–400 degrees Fahrenheit). Throughout the mission, the constant maneuvering of the craft will subject nearly every exterior surface to those ranges of heat and cold. Special effort was required in thermal control to keep electronics from overheating and moving parts from freezing, while minimizing weight and the need for electrical-heater power.

Electronics housings are wrapped in multilayered thermal blankets (see Figure 4-5) that insulate and reflect light. The outer layer of all external blankets is a material called astroquartz. It is similar to glass-fiber cloth, but is better able to withstand intense solar radiation. In fact, chemical binders normally used in astroquartz to control flaking had to be baked out when tests showed that the light intensity at Venus could discolor them and eventually cause a buildup of heat.

The HGA, ALTA, MGA, LGA struts, and propulsion-module structure are painted with a special, inorganic water-based paint, developed at NASA's Goddard Space Flight Center, to withstand and reflect intense solar radiation while minimizing discoloration. Electronics compartments in the FEM and the equipment bus have louvers that open or close automatically to regulate the dissipation of heat from inside the spacecraft. Covering these openings, and also lined up in strips on the solar arrays, are thin mirrors to reflect sunlight. The mirrors have been etched to diffuse reflections that could bake some other exterior part of the spacecraft.

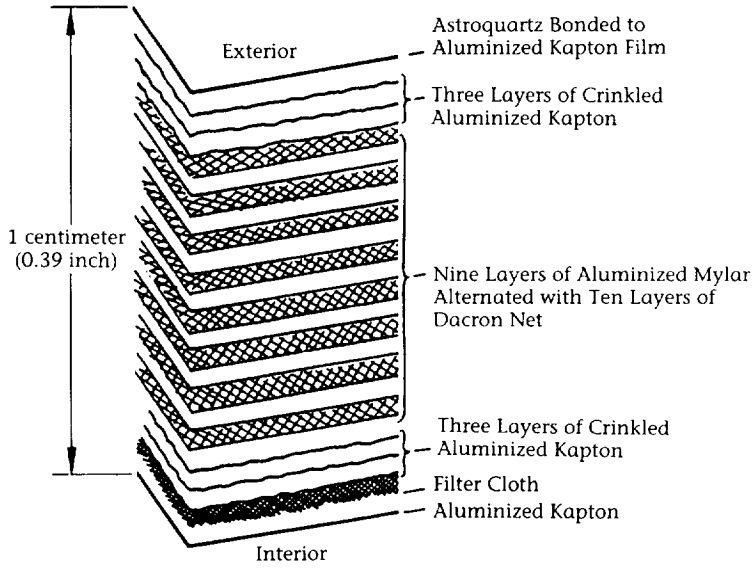

Figure 4-5. Thermal blanket construction.

The net effect of these materials makes the craft tend toward cold temperatures rather than hot. To assure that some cold-sensitive components do not become too cold, flexible electrical heaters have been installed inside housings or wrapped around such fixtures as the solar-panel articulation bearings.

Structure and Mechanisms

Structural design is crucial to an efficient spacecraft design, and Magellan was no exception in this regard. Structures must be strong enough to withstand the *g* forces of launch and orbit insertion and to withstand the tremendous acoustic environment that exists in the shuttle bay during launch. Critical alignment among optical sensors, inertial sensors, and antenna boresights cannot be allowed to suffer significant changes from deformations caused by these environments. All of this has been accomplished on Magellan, without exceeding weight limits imposed by the shuttle or the IUS performance limits, through the efficient use of various structural materials, including aluminum, titanium, beryllium, aluminum honeycomb, and graphite-epoxy composites.

Mechanisms used on Magellan include the hinges used to fold the solar panels in the shuttle bay for launch, retention and release devices used to hold the solar panels during launch, and the solar array articulation joints, including the cable-wrap assemblies, that allow the solar panels to rotate nearly 360 degrees without the use of slip rings. Also used on Magellan are bolts and explosive-actuated release nuts used to hold the spacecraft to the IUS adapter and to hold the SRM to the spacecraft until separation. At separation, such devices as springs and guide pins ensure enough distance between the separated bodies to prevent subsequent collision.

Computing and Software

Magellan's brains are two ATAC-16 computers located in the attitude-control subsystem and four 1802 microprocessors in the distributed CDS. All computers are in a redundant configuration as insurance against a breakdown, are fully reprogrammable, and are modified equipment from the Galileo Project.

Magellan is programmed to do a lot of its own "thinking" if problems arise. Past space missions often produced huddled experts exploring ways of working around a malfunctioning spacecraft. Magellan takes advantage of advances in fault-detection software design to analyze problems that occur and carry out a series of alternative remedies.

Minor or slowly developing problems revealed by telemetry will be managed by ground personnel. However, time-critical or mission-critical malfunctions will be detected, analyzed, and dealt with by two onboard fault-protection software systems: one for attitude control and the other for the rest of the spacecraft.

Problems with the attitude control are treated "holistically" in a full-system health analysis to ascertain the integral cause and remedy. Other spacecraft malfunctions are managed on an individual basis by software in the CDS.

Although some of the spacecraft attitude-control software was inherited from the Galileo mission, most is new because of differences between the control systems and the missions. Ninety percent of the

6,000 lines of code in the attitude-control software is new, including 2,000 lines for fault protection. Of the 18,000 lines of code for the CDS, 45 percent is unmodified Galileo code, 20 percent is new, and 35 percent is modified Galileo code. The fault-protection software resident in the CDS totals 1,500 lines.

Spacecraft operation is controlled for several days at a time by commands sent from Earth and stored in the CDS. During mapping, this method requires accurate navigational data that are updated as frequently as three times a week.

Control of the radar system is performed with data generated by the Radar Mapping Sequencing Software (RMSS) located on Earth. Almost all significant command sequences are stored in a simplified form on mission-control computers at JPL. For most command sequences, engineers simply select from that set and add parameters. Ground computers then convert the sequences into the Magellan command bit patterns for transmission to the spacecraft.

During the interplanetary cruise, these commands will span up to three weeks of activity. During mapping, up to eight days of commands are sent at a time. An extra day is included in every upload to provide a safety buffer if there is a delay in commanding the next upload.

As you can see, the Magellan spacecraft is a marvel of high technology. Its single payload, a radar sensor, and the synthetic-aperture method of radar mapping are both products of equally sophisticated technologies, as we shall see in Chapter 5.

Venus, sweet mystical star
Earthlike, but hotter by far
No use to peruse
Unless you can use
Synthetic-aperture radar

— Anonymous

Chapter 5
The Radar System

The SAR method of generating images is the heart of the Magellan mission. Radar microwave energy will be used to observe the surface of Venus because the visually opaque clouds are transparent to the high radio frequency the radar transmits and receives. The technique of producing SAR images has been known for about 40 years. In most cases, the method uses a radar with a highly directional antenna on a movable platform—usually an aircraft or a spacecraft.

Understanding Synthetic-Aperture Radar

In the way a beam of light pierces darkness and reflects from objects to reveal their position, shape, and texture, Magellan's radar will use microwave energy to observe the surface of Venus. The high-gain and altimeter antennas will transmit the radar pulses (which are in an invisible part of the electromagnetic spectrum) and receive the reflected pulses (called echoes).

The word "aperture" in synthetic aperture refers to the size of the antenna that receives the echoes. As it is with a camera's lens, so it is with a SAR antenna, in that the larger the antenna (aperture), the higher the resolution of the resulting image. Because the antenna moves while it receives the echoes, special processing on Earth can simulate reception by

a much larger antenna (i.e., a synthetic aperture). The distance Magellan travels while a surface feature is within the radar's field of view determines the functional size of the synthetic aperture.

The radar transmits energy in short pulses to one side of the platform, as shown in Figure 5-1. The direction along the track of the platform's motion is called azimuth; the direction across the track is called range. The SAR forms an image strip, with a width determined by the range dimension of the antenna's illumination and a length determined by the time the radar is in continuous imaging operation. The image strip (or swath) produced by Magellan will be about 25 kilometers (16 miles) wide and about 16,000 kilometers (10,000 miles) long.

Did you know . . .

During mapping, the Magellan radar sensor consumes 200 watts of electricity—the equivalent of a bright floor lamp.

The SAR technique requires the radar system to transmit and receive multiple pulses and echoes. If observed on an oscilloscope, one echo looks very much the same as the next, but they have subtle differences caused by the relative motion between the target and the radar. This motion creates an effect similar to the pitch change of a train whistle as a train passes by. This frequency change is called the Doppler effect; this effect is used to sharpen the resolution of an image, but in the azimuth direction only. Conventional pulse encoding and processing establish the resolution in range.

The principal source of noise in most SAR images is self-noise, called speckle. Speckle resembles salt-and-pepper-like changes in image intensity, like those in a poor-quality television picture. In SAR images, speckle is reduced by acquiring and processing the data in several "looks" (independent observations of the same target) and then adding the looks together. Most radar images, including Magellan's, are composed of at least four looks.

The SAR techniques for resolution improvement have been used to image the surfaces of Earth, the Moon, and Venus. An image produced by a SAR is very similar to a traditional aerial photograph, but there are some important distinctions. Areas that are bright in a radar image are

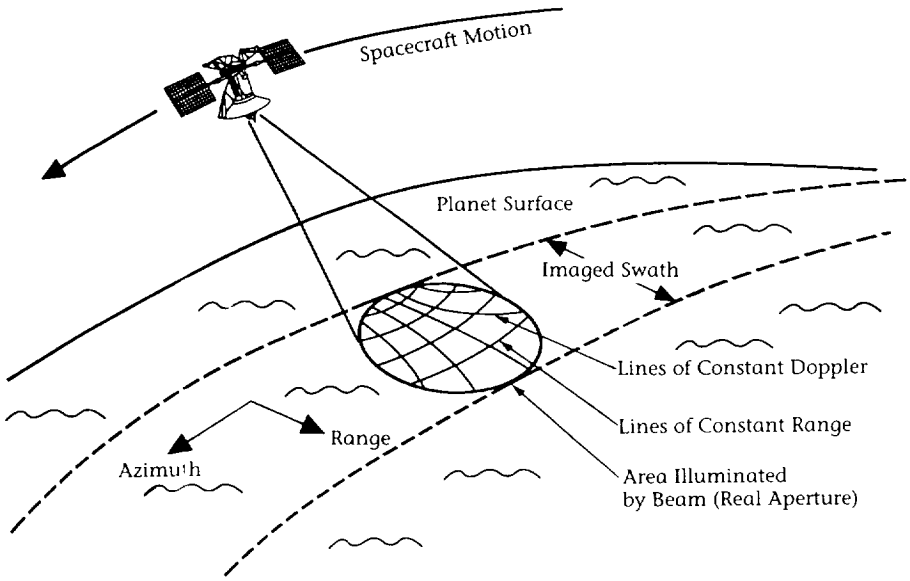

Figure 5-1. To improve azimuth (along-track) resolution, a SAR gathers data while looking to one side of the direction of motion. Magellan normally operates in a left-looking configuration.

not necessarily bright in a traditional photograph. Figure 5-2 shows a picture of the Los Angeles Basin in which the city of Burbank (upper left of center) appears bright in the SAR image. This brightness is caused by the alignment of buildings with the path of the radar platform. The local steep mountains appear to fold over toward the radar because of the shallow (near-vertical) angle between them and the radar. A SAR image shows no vegetation because trees and rocks reflect radar waves in a similar manner and it is difficult to distinguish between them. In most cases, surface roughness determines brightness in a radar image.

Radar images have additional characteristics that distinguish them from visible-light images or photographs. The characteristics of photographs are determined mainly by the direction, relative to the camera, of the source illumination, the color of the subject, and the intensity of the light. Radar images are usually formed from a single-frequency radar; therefore, the images are usually shown in black and white, with these two extremes representing weak and strong signals, respectively. Also, the transmitter (light) and receiver (camera) are usually collocated.

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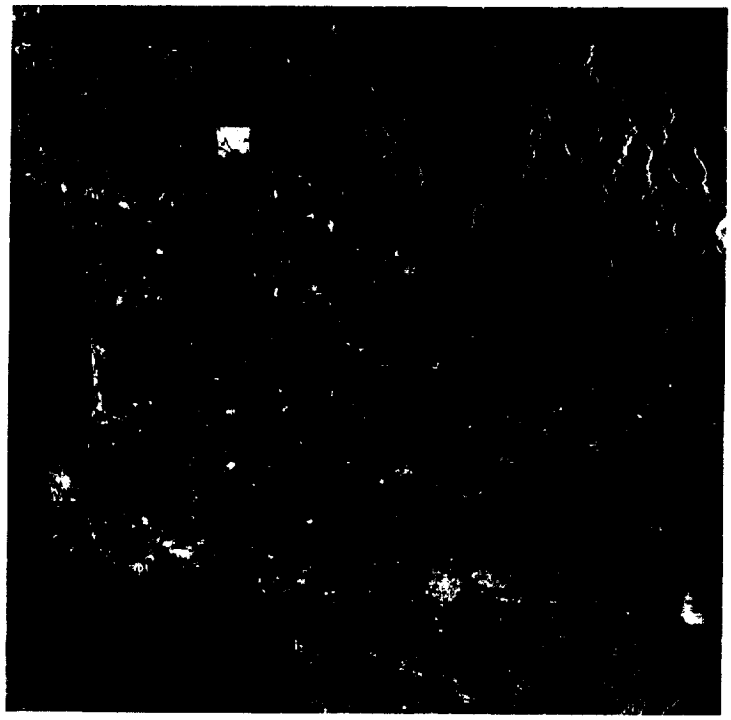
(a)



(b)

Figure 5-2. Although this SAR image of the Los Angeles Basin from a NASA-Seasat image (a) looks like a photograph, there are important differences between it and its optical counterpart (b).

SAR images can be formed using data gathered through clouds, at night, and from under dry, thin layers of sand. Because the brightness in a radar image is a function of surface roughness, angle of incidence, and electrical properties of the surface, radar-image interpretation is very different from that used for normal photographic images. The technique of radar-image interpretation is advancing as we gather data in a variety of ways and use ground truth (local observation) to increase our understanding of the interaction between the radar wave and the surface.

The Radar Sensor

The radar sensor, Magellan's sole scientific instrument, will perform three distinct functions in Venus orbit: SAR imaging (to produce images of surface features), altimetry (to measure the height of surface features), and radiometry (to detect the natural thermal emissions from the planet surface).

The Magellan radar sensor, shown in Figure 5-3, is composed of 17 units racked in a 1.5 × 0.9 × 0.3-meter (5 × 3 × 1-foot) enclosure and weighs 154 kilograms (340 pounds). Most of the units are in redundant pairs for higher reliability. The sensor is located within the spacecraft's FEM and is used in combination with the high-gain and altimeter antennas.

A combination of factors led to the major mission constraints listed in Table 5-1. In many ways, these constraints dictated the design of the radar system and presented some pretty unique challenges. The high-gain antenna and the elliptical orbit were the most demanding challenges from the system-design view. The requirements imposed on the design were to meet all science objectives within the mission constraints and to make efficient use of the limited resources, especially the rate at which the spacecraft sent data to Earth.

The high-gain antenna is excellent for telecommunications, but is uncommon for use as a SAR antenna. SAR antennas usually are larger and can be directed without moving the spacecraft. The fact that the antenna is rigidly fixed to Magellan's structure complicated the design of the spacecraft attitude-control system because the antenna, and thus

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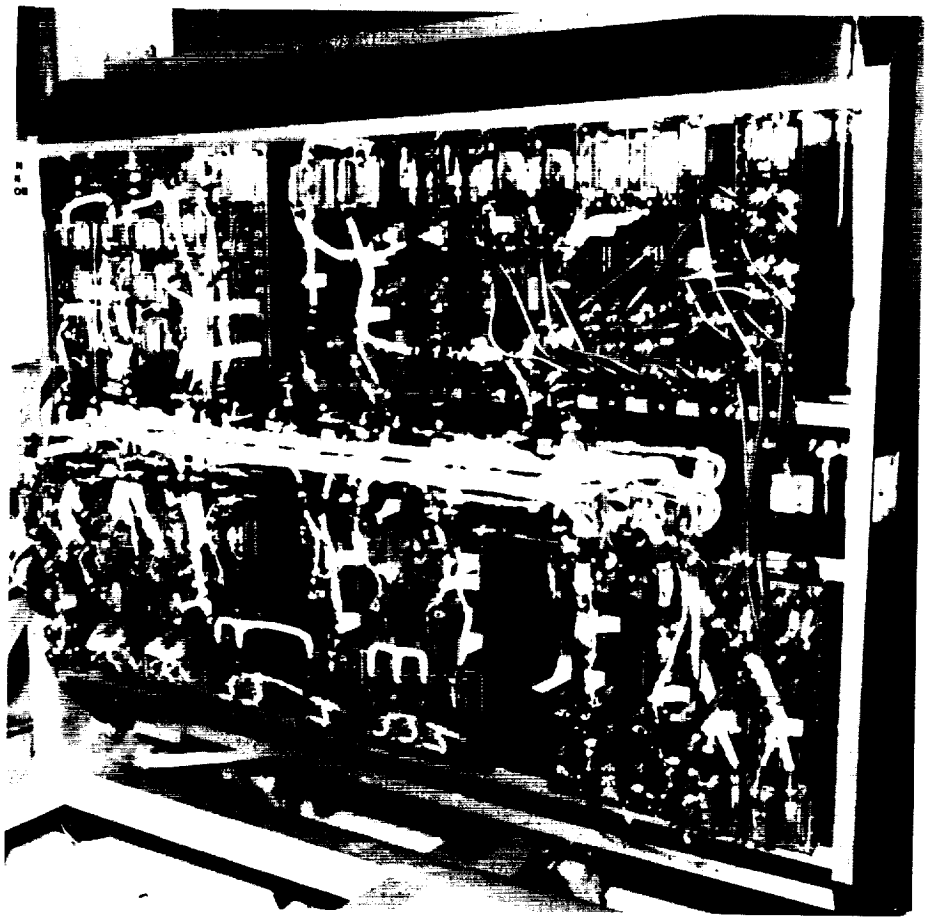

Figure 5-3. The complete radar sensor.

the spacecraft, must be turned continuously during each orbit for mapping and communications with Earth, as well as for calibrations to aid navigation and to maintain proper spacecraft attitude. Additionally, the sharing of this antenna with the telecommunications subsystem reduced the number of possible design options that could have better tailored the antenna to the Magellan radar use.

The elliptical, 189-minute orbit is a definite departure from previous experience with orbiting radars, which usually operate in near-circular orbits. Since a SAR requires an extended series of pulses and echoes to form the synthetic aperture, the echoes must be interleaved between the transmitted pulses because the radar cannot transmit and receive

Table 5-1. Magellan Mission Constraints That Influenced Radar Design

A single, spacecraft-fixed high-gain antenna
An elliptical orbit
Data rate and volume limitations
Radar commanding from stored sequences only

simultaneously. To do this, the range to the surface must be predicted with high precision from second to second, which is not necessary for a radar in a circular orbit. Magellan's 44-minute mapping period starts near the north pole at an altitude of about 2,150 kilometers (1,336 miles), continues through periapsis at a 275-kilometer (171-mile) altitude, and finishes at a 2,400-kilometer (1,491-mile) altitude near 74°S latitude. During this time, the radar system must compensate for Magellan's changing speed, changing altitude, and large variations in the planet terrain with adjustments in transmission rate and the echo-receive window. To do this, the system makes an incredible 3,000 changes in its operating mode during each mapping period. The commands that generate these changes are stored in the spacecraft computers and are repeated during each orbit until a new set of commands is received from Earth every few days. The new commands take into account the gradual changes in the orbit and planet terrain.

The constraint of using only stored commands meant that the radar sensor could be of simple design, but that its operation would have to depend on such "outside" functions as navigation for orbit predictions and spacecraft attitude control for its high-precision operation and pointing information.

The inherently high data rate of the SAR system had to be reduced to satisfy the fixed data-rate constraint imposed by elements of the spacecraft's data-handling and transmission system. The record (data-acquisition) rate is approximately 800 kilobits per second and the total volume is approximately 1.8×10^9 bits per orbit. Because of communications link limitations, this amount of data cannot be played back at the recorded rate; the tape recorders are therefore slowed by a factor of

three, and 114 minutes of the 189-minute orbit are used for data playback. Additionally, the radar system employs a "burst-mode" data-acquisition scheme (a data-reduction method discussed below) and passes the data through a digital filter that reduces the data rate but does not sacrifice image quality.

Burst-Mode Data Collection

The *pièce de résistance* of the burst-mode method of data collection is its ability to *quickly* change configurations to accommodate the elliptical orbit and make efficient use of the data volume that can be sent to Earth.

The SAR, altimeter, and radiometer modes share a time slot called the burst period, which lasts less than one second (see Figure 5-4). First, in SAR mode, the radar sends out a rapid burst of pulses through the high-gain antenna. Traveling at the speed of light, the pulses strike Venus' surface and echo back to the antenna. Because of the long burst duration of this mode, the echoes must be interleaved with the transmit pulses. The SAR mode lasts up to 250 milliseconds. After the last echo has been captured, the radar emits another, more-rapid burst of pulses, this time through the altimeter antenna. All of the altimetry pulses are sent before the first altimetry echo returns. This altimeter mode takes up to 25 milliseconds. After this mode, the radar switches back to the high-gain antenna for the radiometer mode. For the next 50 milliseconds, the

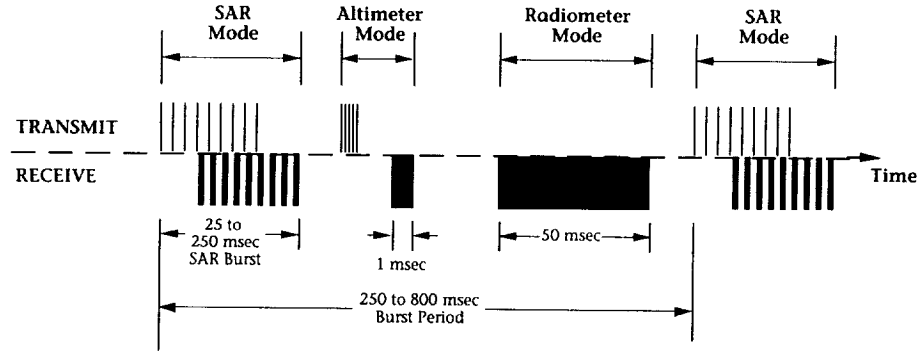

Figure 5-4. Burst-mode data acquisition. The SAR, altimeter, and radiometer modes share a time slot called the burst period, which lasts less than one second.

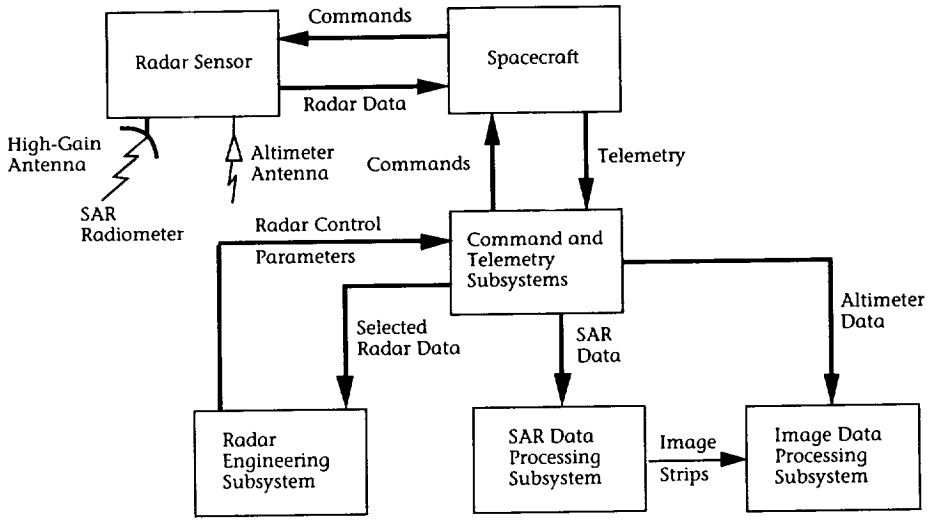

Figure 5-5. The Magellan radar system.

radar becomes a passive receiver of microwave energy naturally emitted from the planet surface.

Magellan is not the first spacecraft to use SAR, but the design of its radar system is clearly the most advanced for its intended purpose.

In addition to the flight equipment (radar sensor and antennas), the radar system includes the Earth-based elements shown in Figure 5-5. Radar-system commands are generated through a computer program called Radar Mapping Sequencing Software (RMSS), which is specially tailored to optimize the data-collection geometry and calculate the nearly 3,000 commands required to operate the radar sensor during mapping. The radar commands are part of the command loads discussed in Chapter 12. Also, a portion of the data returned to Earth, along with engineering information about voltages, currents, and temperatures, is sent to the Radar Engineering Subsystem, where the data-collection process and the health of the sensor can be monitored.

The Earth-based systems also include the SAR Data Processing Subsystem (SDPS), which accepts the raw radar data on magnetic tape. These data are still just the raw-data echoes, which are combined in a complex way (creating the synthetic aperture) to produce image strips. Radiometer data are also processed in this subsystem.

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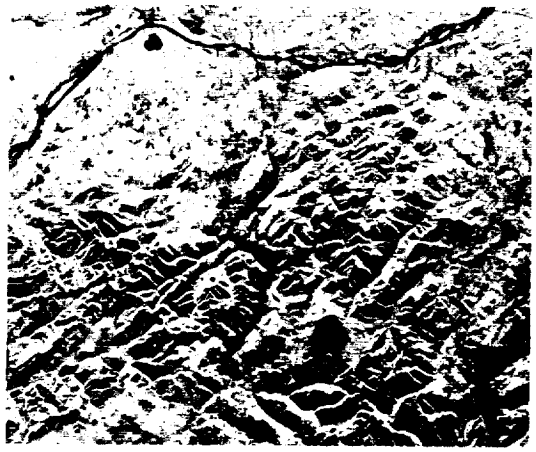
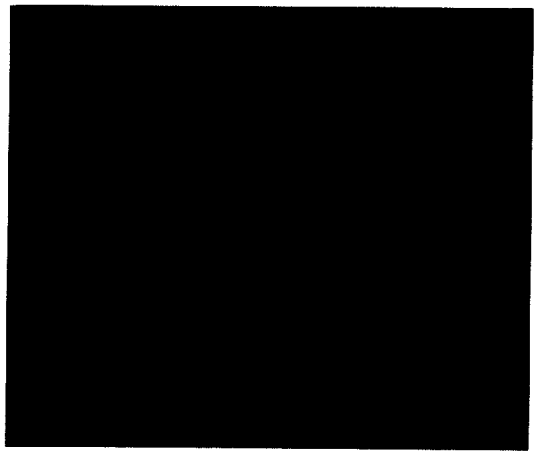
Figure 5-6. The evolution of imaging radar is illustrated in these images of the Mount St. Helens region of Washington, which are simulations derived from the radar-imaging data acquired by the Seasat satellite. The still-active volcano does not show at the Pioneer Venus resolution. Although the feature is visible at the Venera resolution, it is not possible to tell whether it is a volcano or a meteorite impact crater.

Mount St. Helens



Magellan resolution

Venera resolution



Pioneer resolution

The Image Data Processing Subsystem (IDPS) takes the image strips in electronic form (on tape or discs) and mosaics these strips into large-area-coverage maps of the planet surface. The radiometer data are likewise mosaicked into maps. The altimetry data are accepted by the IDPS, and both raw-data processing and mosaicking are performed to produce large-area-terrain height maps that will complement the image data mosaics from the SAR.

Engineers from the Hughes Aircraft Company of El Segundo, California, and from JPL folded in all of these mission constraints; what emerged was a fairly simple radar sensor, an innovative design for the system that operates it, and a SAR-image resolution of the Venusian surface that is higher than any achieved to date (see Figure 5-6).

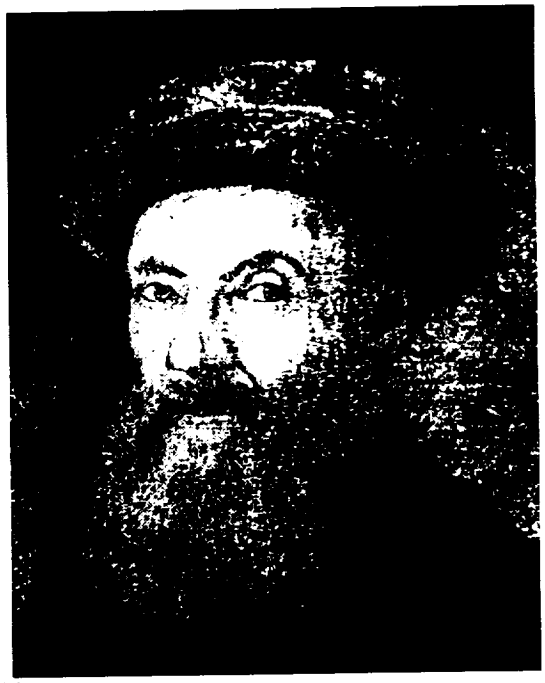
Ah me! What a world this was to live in two or three centuries ago, when it was getting itself discovered.

— Alexander Smith

Chapter 6

Ferdinand Magellan— The Project's Namesake

Ferdinand Magellan grew up in an age of discovery. Born in Northern Portugal around 1480, Magellan belonged to a romantic era of the sea during which Bartholomeu Dias rounded the Cape of Good Hope, Vasco da Gama reached India, and Columbus and Vespucci made their historic voyages.



As a young man, Magellan gained maritime experience with Portuguese naval fleets in India, Asia, and the Moluccas (Spice Islands) in Indonesia. Although the war chronicles of that period seldom mentioned his name, he achieved the rank of captain by the time he was 30 years old and became one of the most experienced navigators of his time.

However, when Magellan and other battle-scarred

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soldiers and sailors returned home to Portugal, they received little thanks for the numerous victories that had brought enormous wealth and prestige to their king and countrymen. Magellan's noble though low-grade birth entitled him to a beggarly allowance, a pompous, meaningless title, and the right to become a loafer at court—an unbearable situation for a man of honor and ambition.

The first opportunity for renewed military service found Magellan fighting the Moors in Morocco, but that, too, ended in hardship. A lance wound permanently injured his left leg, and an unjust accusation of trading with the enemy scarred his reputation. After King Emanuel of Portugal coolly rejected Magellan's petition for a post within the royal navy, the soldier renounced his loyalty to Portugal and left for Spain.

It was the feverish quest for spices that inspired Emperor Charles V of Spain to financially support Magellan's claim of a western route to the Spice Islands through a seaway near the southern tip of South America. On the gray morning of September 20, 1519, Magellan's fleet of five small ships and a crew of 265 men departed from Sanlúcar de Barrameda on an around-the-world voyage. His flagship, Trinidad, was accompanied by Concepción, San Antonio, Victoria, and Santiago.

From the frigid waters of southern latitudes, through the strait that was to bear his name, Magellan's steely resolve and unyielding perseverance enabled him to face and conquer treacherous seas, dangerous passages, and mutinous crews. Sickness and starvation claimed the lives of 19 men during the 3 months and 20 days Magellan's fleet sailed a sea much broader than expected. Since not one storm was encountered during that period, they named the ocean "Pacific," meaning "peaceful."

Finally, on March 6, 1521, a cry of "Land ho!" boomed from the masthead. Though Magellan had reached what is known today as the Philippines, he knew that the Spice Islands and victory were within easy reach.

But once again, fate delivered its now-familiar decree: Magellan would bear the burdens, but would never enjoy the fruits of success. A single act of poor judgment caused the downfall of Ferdinand Magellan. He was fatally wounded on April 27, 1521, after becoming involved in a dispute between warring Philippine tribes. It was an ironic ending for

one who had survived an expedition that had unceasingly taxed his intellect and intuition, a man whose character was so strikingly identified by caution and foresight.

Only one ship, the Victoria, and 18 of the original crew members returned to Spain, thereby completing the first circumnavigation of the globe. Though Magellan's route proved impractical for the spice trade, his voyage has been called the greatest single human achievement on the seas. He was never granted the dazzling fame bestowed on other explorers of the period, but Ferdinand Magellan's legacy changed man's understanding of his world.

Art is I; science is We.

— Claude Bernard

Chapter 7
The Science Investigators

The Radar Investigation Group

The Magellan Radar Investigation Group (RADIG), selected by NASA in 1979 for the earlier VOIR mission, has the major responsibility for the radar science of the Magellan mission. To make sure that all aspects of the mission are capable of producing results that satisfy the scientific objectives, members of the RADIG have participated in most of the decisions about how the radar was designed and how it will be used. The RADIG has also been involved in laying out the data-processing procedures and in the decisions about how the data will be finally presented. One of its most important tasks, of course, will be to interpret the data and publish the results of its studies.

The RADIG is a collection of 26 scientists and engineers (see Table 7-1) with various perspectives and fields of expertise. Of these, five are foreign residents and supported by their own governments. An attempt will be made to coordinate each scientist's research activities so that, in sum, the major questions about the geology, geophysics, geochemistry, and geological history of Venus will be addressed.

Because of the large size of the RADIG membership, an executive subset—the Project Science Group (PSG, identified in Table 7-1)—has

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Table 7-1. RADIG Members

Team Member		Affiliation
Raymond E. Arvidson	(PSG[a])	Washington University
Victor R. Baker		University of Arizona
Joseph H. Binsack		Massachusetts Institute of Technology
Joseph M. Boyce	(PSG)	National Aeronautics and Space Administration
Donald B. Campbell		Cornell University
Merton E. Davies	(PSG)	The RAND Corporation
Charles Elachi	(PSG)	Jet Propulsion Laboratory
John E. Guest		University of London
James W. Head III	(PSG)	Brown University
William M. Kaula		University of California, Los Angeles
Kurt L. Lambeck		Australian National University
Franz W. Leberl		Vexcel Corporation
Harold Masursky	(PSG)	U.S. Geological Survey
Dan P. McKenzie		Cambridge University
Barry E. Parsons		Oxford University
Gordon H. Pettengill[b]	(PSG)	Massachusetts Institute of Technology
Roger J. Phillips	(PSG)	Southern Methodist University
R. Keith Raney	(PSG)	Canada Centre for Remote Sensing
R. Stephen Saunders[c]	(PSG)	Jet Propulsion Laboratory
Gerald G. Schaber		U.S. Geological Survey
Gerald S. Schubert		University of California, Los Angeles
Laurence A. Soderblom	(PSG)	U.S. Geological Survey
Sean C. Solomon	(PSG)	Massachusetts Institute of Technology
Manik Talwani		Houston Area Research Center
G. Leonard Tyler	(PSG)	Stanford University
John A. Wood		Smithsonian Astrophysical Observatory

[a] Project Science Group.
[b] Principal Investigator.
[c] Project Scientist.

been chosen to represent RADIG; the PSG has met quarterly during the years prior to launch and will continue to meet throughout mapping operations.

The Data Products Working Group and the Mission Operations and Sequence Planning Working Group were established by the PSG to approve the Project's plans for data products and spacecraft/radar operations, respectively.

To accomplish its assignment, the RADIG is organized around six groups, each responsible for a general task (see Figure 7-1).

The Cartography and Geodesy Task Group will develop a latitude and longitude grid (known as a geodetic control network) for Venus by which Magellan maps of the planet may be coordinated and from which improved estimates of Venus' pole position and rotation rate may be derived.

The Surface Electrical Properties Task Group will work with the radar-scattering intensities obtained from both the SAR and altimetry operating modes, as well as with the thermal-emission data obtained from the radiometry mode, to determine the electrical properties of the surface.

The Geology and Geophysics Task Group is charged with meeting the scientific objectives that are the core of, and have largely justified, the Magellan mission. With 19 members, it is the largest of the task groups. Because of its size, it has been divided into four subgroups: (1) Volcanic and Tectonic Processes, (2) Impact Processes, (3) Erosional, Depositional, and Chemical Processes, and (4) Isostatic and Convection Processes. While these specialized processes provide a convenient framework, it is recognized that many, if not most, studies of the Venusian surface and interior will embrace more than one of them. Participation in these subgroups, and the consequent division of effort among the task groups' membership, will be fluid.

The System Calibration and Test Task Group monitors the radar test procedures and associated support equipment. While not carrying the prime responsibility for the performance of the radar system, this group provides advice from the users' point of view and will attempt to make sure that the calibration and performance of the radar meet the needs of the scientists.

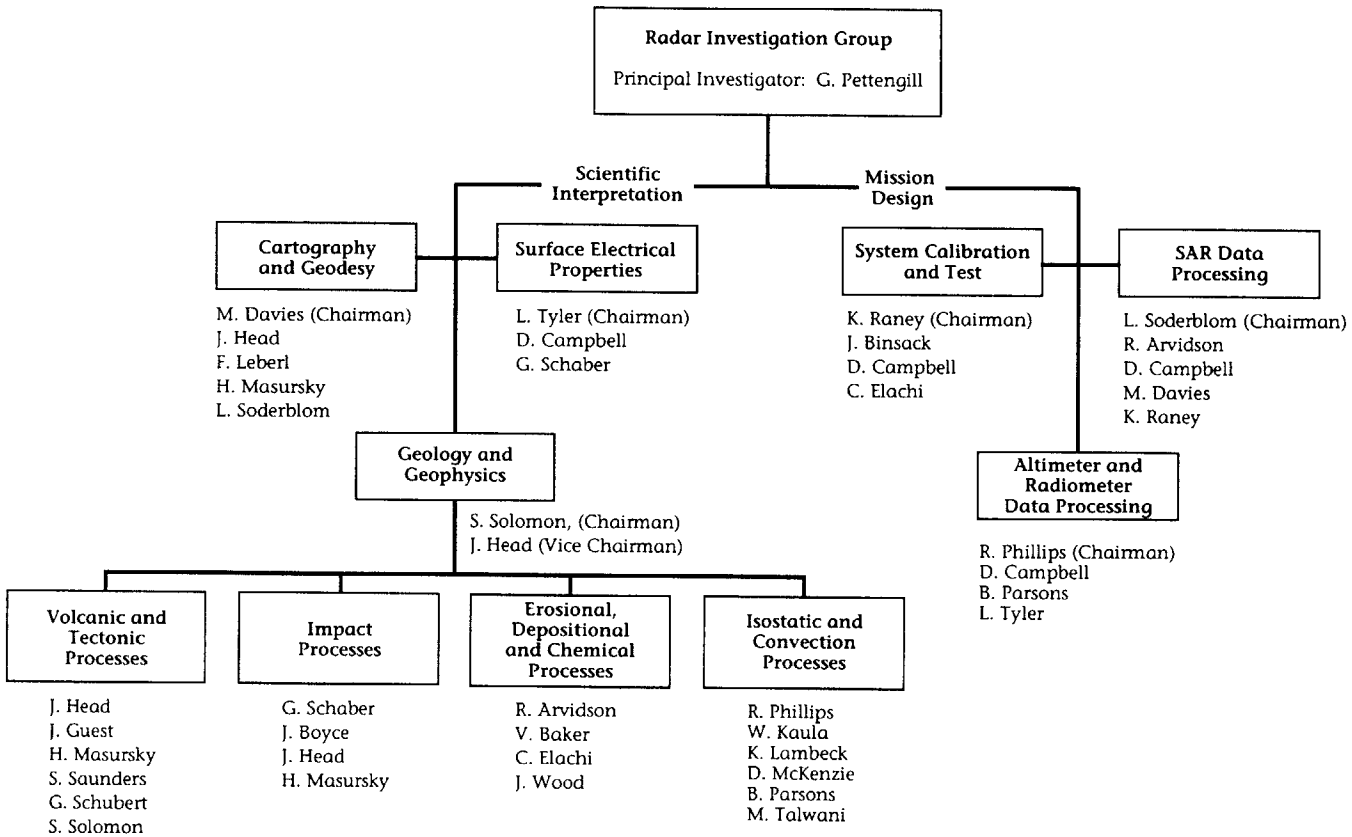

Figure 7-1. RADIG organization.

The SAR Data Processing Task Group is charged specifically with monitoring the design of the algorithms and data flow involved in the handling of the SAR data by JPL's Multimission SAR Processing Facility.

Finally, the Altimeter and Radiometer Data Processing Task Group monitors the algorithms and data flow from the altimetry and radiometry experiments through the various processing steps to a final product.

The Gravity Investigation Group

Gravity and altimetry data from the Pioneer Venus Orbiter (PVO) mission (1978–1982) have provided the foundation for the present geophysical models of the interior of Venus. These data show a significant link between the variations in the gravity field of Venus and its topography; this link does not exist on Earth, the Moon, or Mars. This suggests that there are major differences between the processes acting within Venus and those operating within these other planetary bodies.

The primary objective of the Magellan Gravity Investigation Group (GRAVIG) is to enhance the existing data set so that more detailed gravity modeling can be performed.

However, unlike the radar experiment, which will receive high-resolution data during Magellan's initial 243-day mapping cycle, the gravity experiment will have to wait for an extended-mission phase to obtain its best data. The reasons for this are explained by the nature of the gravity data, the way in which these data are obtained, and the fact that the instrument of the gravity investigation is the Magellan spacecraft itself.

As Magellan orbits Venus, it will experience slight variations in speed caused by surface features and/or density variations within the planet. It is these changes in speed that form the basis of the gravity data.

To detect these variations, an Earth-based radio tracking system must precisely measure the spacecraft's velocity every few seconds, which requires Magellan's high-gain antenna to be pointed toward Earth so that it serves as a tracking transponder.

The highest-resolution gravity data will be obtained when the spacecraft is at its closest range (periapsis) to Venus. But during the initial

mapping cycle, the time around periapsis will be dedicated to SAR imaging with the high-gain antenna pointed toward the surface of the planet, making it impossible to obtain high-resolution gravity data during that phase of the mission.

This does not mean that gravity data will not be obtained in the first mapping cycle. For approximately 2 hours of each mapping pass, high-altitude velocity data, which results in lower-resolution gravity data, will be acquired during the normal tracking activities while the spacecraft is transmitting radar data to Earth. These low-resolution data will be used in conjunction with PVO data to produce a revised model for the global gravity field of Venus.

Scientists from both RADIG and GRAVIG will work together to develop models of the interior of Venus. These models will incorporate SAR and altimetry measurements of the surface of the planet as well as deductions based on studies of the SAR images. These models, in turn, will help scientists develop scenarios for planetary formation and thermal history and will serve as an important source of information for comparative planetology studies.

The Gravity Investigation Group is composed of two teams of American and French scientists (see Table 7-2), who will use different approaches to analyze the Magellan gravity data. The use of independent analysis techniques will provide important cross-checks on the calculations and will improve our confidence in the estimated gravity-field parameters and modeling results.

The French GRAVIG members reside in Toulouse, France. All costs of the French team, such as salaries, travel, and data analysis, are paid by the French government.

Guest Investigators

Seventeen additional science investigators (see Table 7-3) have been selected for the Magellan Project through the Magellan Guest Investigator Program. These scientists, representing a wide variety of disciplines, will be integrated into the Project's operations and science-analysis efforts.

Table 7-2. GRAVIG Members

Team Member		Affiliation
William L. Sjogren[a]	(PSG[b])	Jet Propulsion Laboratory
Mohan Ananda		Jet Propulsion Laboratory
Georges Balmino[a]	(PSG)	Centre National d'Etudes Spatiales
Nicole Borderies		Centre National d'Etudes Spatiales
Bernard Moynot		Centre National d'Etudes Spatiales

[a] Principal Investigator.
[b] Project Science Group.

Table 7-3. Magellan Guest Investigators

Name	Affiliation
E. L. Akim	Keldysh Institute of Applied Mathematics, U.S.S.R.
Neon E. Armand	Institute of Radiotechnology and Electronics, U.S.S.R.
Alexandr T. Basilevsky	Vernadsky Institute of Geochemistry, U.S.S.R.
W. Bruce Banerdt	Jet Propulsion Laboratory
Richard M. Goldstein	Jet Propulsion Laboratory
Ronald Greeley	Arizona State University
Randolph L. Kirk	U.S. Geological Survey
Michael C. Malin	Arizona State University
George E. McGill	University of Massachusetts
Henry J. Moore	U.S. Geological Survey
Duane O. Muhleman	California Institute of Technology
David Sandwell	Scripps Institute
Peter Schultz	Brown University
Virgil L. Sharpton	Lunar and Planetary Institute
Steven W. Squyres	Cornell University
John Suppe	Princeton University
Donald L. Turcotte	Cornell University

One of the few, the immortal names,
that were not born to die.

— Fitz-Greene Halleck

Chapter 8
What's in a Name?

There is more than you might expect, if you are talking about the names of features on Venus. From the earliest times, Venus has been associated with goddesses of love and beauty. Mystery, another feminine attribute, is also evident—a thick atmosphere of swirling clouds veils its surface from view.

It seems appropriate, then, that the International Astronomical Union (IAU), the governing body for planetary and satellite nomenclature, adopted a theme in keeping with the age-old feminine mystique of Venus: features would be named for women, both mythological and real, from the mythologies and histories of ethnic groups throughout the world (see Table 8-1).

Each feature name has two parts: a female name, e.g., "Aphrodite," plus a feature class, e.g., "Terra" (continent). Although most of the assigned names are female, three previously adopted names were retained. "Alpha" and "Beta," the first names applied to Venusian features, became "Alpha Regio" and "Beta Regio," two areas of subdued to moderate topographic relief that rise above the widespread Venusian plains. "Maxwell" also was retained for "Maxwell Montes," the highest region on Venus. James Clerk Maxwell is thus the only man honored with a feature name. Those within the IAU who favored the retention of

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Table 8-1. Categories for Naming Features on Venus

Feature	Definition	Category
Chasmata	Canyons	Goddesses of hunt; moon
Colles	Small hills, knobs	Sea goddesses
Coronae	Ovoid-shaped features	Fertility goddesses
Craters (large) (small)	Craters Craters	Famous women Female first names
Dorsa	Ridges	Sky goddesses
Lineae	Elongate markings	Goddesses of war
Montes	Mountains	Goddesses, miscellaneous (also, one male radar scientist)
Paterae	Irregularly shaped craters	Famous women
Planitiae	Low plains	Mythological heroines
Planum (1 only)	High plain	Goddess of prosperity
Regiones	Areas of moderate relief	Giantesses and Titanesses (also two Greek alphanumeric designations)
Rupēs	Scarps	Goddesses of hearth and home
Tesserae	Polygonal ground; tiles	Goddesses of fate or fortune
Terrae	Continents	Goddesses of love
Tholi	Domical hills	Goddesses, miscellaneous

his name argued that all the early information about Venus, including its size, rotation, and major features, was obtained from radar observations, and that Maxwell formalized the mathematics of the principles that made these observations possible. The rest of the names are feminine, and they honor a worldwide assemblage of nationalities and ethnic groups, in accordance with IAU requirements.

An imaginary tour around the planet evokes memories of some of the most notable women of history and mythology. Continent-sized highland areas (terrae) are named for counterparts of Venus, the Roman goddess of love (see Figure 8-1). The northern highland, Ishtar Terra, honors the Babylonian goddess of love (and war). As early as 1800 B.C., the Babylonians gave the name of their goddess of love to the beautiful

Figure 8-1. Venus, the Roman goddess of love.
(Courtesy of Hamlyn Publishing Co., London.)

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morning and evening "star." An ancient Babylonian psalm provides a glimpse of her:

"By causing the heavens to tremble
and the Earth to quake,
By the gleam which lightens the sky,
By the blazing fire which rains upon
a hostile land,
I am Ishtar."

Admittedly this sounds a little more warlike than loving! Aphrodite is the Greek goddess of love (see Figure 8-2); the name (which literally means "sea foam," because the goddess was born from the sea) brings to mind Botticelli's painting, "The Birth of Venus," which hangs in the Uffizi Gallery in Florence, Italy.

The western part of Ishtar Terra is a high volcanic plateau, Lakshmi Planum, named for the Indian goddess of prosperity and fortune. Lakshmi may turn out to be an extremely active place, since it contains two calderas of probable volcanic origin.

The calderas (paterae) are named for famous historical women: Colette, the French writer who wrote convincingly about the pleasure and pain of love; and Sacajawea, the highly intelligent American Indian guide who helped Lewis and Clark explore the regions of the Louisiana Purchase. West and north of Lakshmi Planum are mountain belts (montes) named for goddesses of any type; these honor Freyja, Norse mother of the great god Odin, and Akna, a Mayan goddess of birth. The southern boundary of Lakshmi Planum consists of fault scarps (rupēs) named Vesta for the Roman hearth goddess and Ut for the Siberian goddess of the hearth fire. Vesta was represented by an eternal flame tended by six maidens of high birth, the vestal virgins or "keepers of the flame."

Continuing to the south and east, one passes through low plains areas (planitiae) that are named for mythological heroines. Helen honors the Greek woman whose face "launched a thousand ships," and Sedna reminds one of the little drowned Eskimo girl whose fingers became the first seals. Canyons (chasmata) on the Venusian surface are

Figure 8-2. Aphrodite, the Greek goddess of love.
(Courtesy of Hamlyn Publishing Co., London.)

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named for either goddesses of the hunt or moon goddesses; in mythology, these attributes are often combined in the same goddess. Diana was a Roman huntress; her chasma, in Aphrodite Terra, includes some of the lowest elevations of Venus.

Irregular, long regions (lineae) are named for warlike mythological women. Hippolyta Linea is an example. Hippolyta was Queen of the Amazons and wife of Theseus.

Regiones are circular areas of moderate topographic relief. Aside from Alpha and Beta, they are named for Titanesses; Atla, part of Aphrodite Terra, is named for the mother of Heimdall, the Norse god of light. Circular features were recognized on the early radar reflectivity maps of Venus, but their origin is still uncertain. In the late 1970s, the PVO radar resolution made possible an attempt to differentiate between

Figure 8-3.
Judith A. Resnik.
(Courtesy of NASA/
Johnson Space Center.)

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volcanic features (paterae), discussed above, and impact craters, which were to be named for notable deceased women. A few names were applied to craters on the basis of those data: Meitner Crater honors the famous Austrian physicist, and Nefertiti Crater honors the beautiful wife who supported Pharaoh Akhenaten's attempt to install monotheism in Egypt. Since then, two additional names were added by the Soviets, based on Venera 15 and 16 data: Resnick Crater and McAuliffe Crater honor the astronaut (see Figure 8-3) and educator (see Figure 8-4), respectively, who perished in the explosion of the Space Shuttle Challenger in 1986.

The central peak of another crater, located in Alpha Regio, was originally used to define zero longitude; this peak is named Eve. When the Soviet Venera missions were completed in the early 1980s, another

Figure 8-4.
Sharon Christa McAuliffe.
(Courtesy of NASA/ Johnson Space Center.)

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small crater, Ariadna, superseded Eve as the definition for zero longitude. This change has led to some confusion; it is likely that a third crater nearer the equator will be nominated from the higher resolution and more extensive data of the Magellan mission.

The Venera missions also produced two new feature terms: "coronae," for ovoid structures, and "tesserae," for mosaiclike terrain, were adopted to describe terrain unlike any seen on other extraterrestrial surfaces. An additional 320 names were added to identify features in these new categories, and the ethnic representation was similarly enlarged: Bachue (Corona) is the fertility goddess of the Chibcha Indians; the three Greek Fates—Atropos, Clotho, and Lachesis (Tesserae)—are now honored on Venus. Other features are named using terms transferred from established planetary nomenclature: two features, Akkruva Colles and Jurate Colles are named for sea divinities; fault systems (fossae) are named for warlike persons, such as the Celtic warrior queen, Arionrod; domical small hills (tholi) are named for miscellaneous personages such as Semele, the Phrygian earth goddess. The Soviets also refined the nomenclature of circular features by giving female first names to small craters: Tunde (Hungarian), Nana (Serbo-Croatian), and Selma (Swedish).

When Magellan reaches Venus, a large number of additional names unquestionably will be needed to identify features discriminated by its sophisticated radar sensor. Once again, the names will be feminine, and newly defined features on Venus will be given the names of real and mythical women renowned on Earth.

We must ask where we are and whither we are tending.

— Abraham Lincoln

Chapter 9
From Earth to Venus

Once the spacecraft and the radar system were ready for the mission objectives, we were prepared to get under way with the mission timeline, or itinerary (see Figure 9-1).

Launch

The alignment of Earth and Venus dictated that Magellan be launched between April 28 and May 29, 1989, with the best launch occurring on May 5. (The advantage of a May 5 launch date would become apparent during the VOI maneuver, when the fixed performance of the SRM would be the exact value required to put Magellan into the desired orbit.) The Mission Design Team had skillfully maximized the number of possible launch days so that delays caused by weather or shuttle problems would not prevent a launch. The next few paragraphs attest to the wisdom of this planning effort.

The Space Shuttle Atlantis was moved to Launch Pad 39B at Cape Canaveral, Florida, on March 22, 1989, and the Magellan/IUS combination was installed in the cargo bay on March 25.

In preparation for launch activities, Magellan team members from JPL who were part of the launch team assumed their command posts at the Kennedy and Johnson Space Centers. During the preceding months,

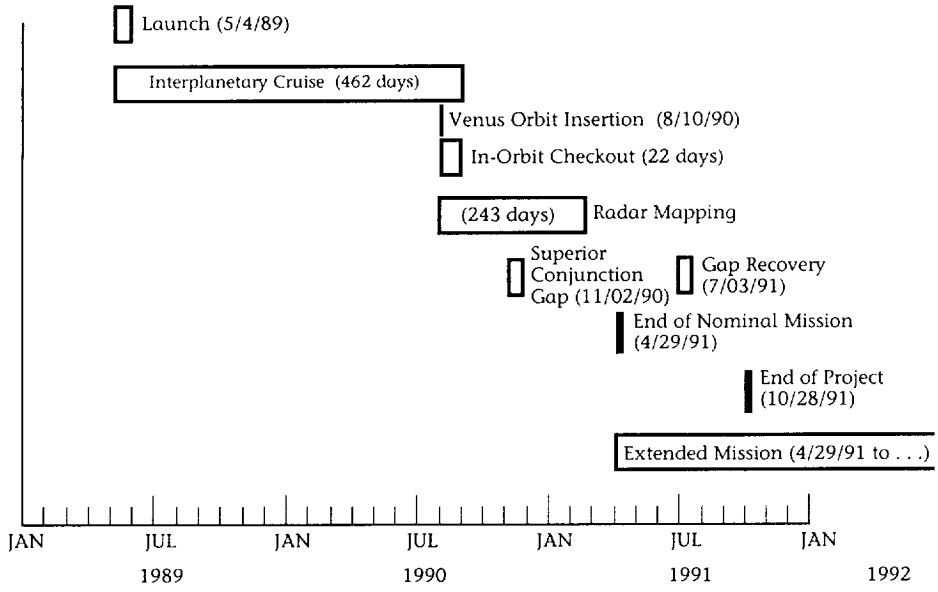

Figure 9-1. Magellan mission timeline.

they and representatives from these other two NASA centers underwent extensive training for the launch event. Other team members remained at JPL to monitor the spacecraft's state of readiness as it rested inside the shuttle's cargo bay. Magellan team members across the country shared the excitement as the launch status remained green (for "go"). Five people who couldn't be more ready were the STS-30 Atlantis astronauts: Captain David M. Walker, Commander; Colonel Ronald J. Grabe, Pilot; and Mission Specialists Mary L. Cleave, Ph.D., Major Mark C. Lee, and Norman E. Thagard, M.D.

The countdown began April 24 and proceeded smoothly toward an April 28 launch. On the 28th, however, with the countdown at Launch –31 seconds, the automatic ground software system detected a shuttle problem and the countdown came to a halt. A hydrogen recirculation pump that cooled the shuttle engines prior to firing developed a short and stopped. The launch on this day was scrubbed.

After careful review of the pump problem and of a second problem involving abnormal venting of a hydrogen circulation line, the launch team selected May 4 for the next attempt.

The countdown resumed, starting this time at Launch –2 days, and proceeded smoothly. But May 4 did not dawn as a likely day for a launch. The sky was overcast, and strong crosswinds (greater than 12 knots) blew across the runway at the Kennedy Space Center's emergency landing site. No one was surprised when a hold for weather was called at Launch –5 minutes.

Fortunately, a 64-minute launch window had been designed for May 4. After 59 anxiety-filled minutes, the winds dissipated and the clouds parted just enough for launch at 2:46:59 p.m., eastern daylight time (see Figure 9-2), only 5 minutes before the end of the launch window for that day. The shuttle slowly rose out of the billows of steam and accelerated toward the low clouds. It went briefly out of sight and then reappeared for a few seconds, framed in a blue window amid the clouds. It was truly picture perfect.

The Space Shuttle Atlantis compensated for the delay in launch by yaw steering into the correct orbit plane. After five revolutions around the Earth at an altitude of 296 kilometers (160 nautical miles), Magellan was slowly deployed from the shuttle (see Figure 9-3). Sixty minutes later, with the solar panels extended as shown in Figure 9-4, the IUS ignited its two SRMs in rapid succession and propelled the spacecraft on very nearly the precise trajectory to Venus. After firing its attitude-control thrusters for a small course correction, the IUS separated from Magellan and used its remaining fuel to move away from the spacecraft.

Figures 9-3 and 9-4 are two photographic mementos the astronauts brought back to the Magellan team.

Magellan's Path to Venus

The original May 1988 launch period would have allowed Magellan to reach Venus 4 months later via a Type-I trajectory, meaning that from launch to destination, the spacecraft would have traveled less than 180 degrees around the Sun. There was a similar opportunity in the October 1989 launch period initially set aside for Magellan but subsequently assigned to the Galileo mission to avoid further delays in *its* launch.

Figure 9-2. The Space Shuttle Atlantis/Magellan launch on May 4, 1989.

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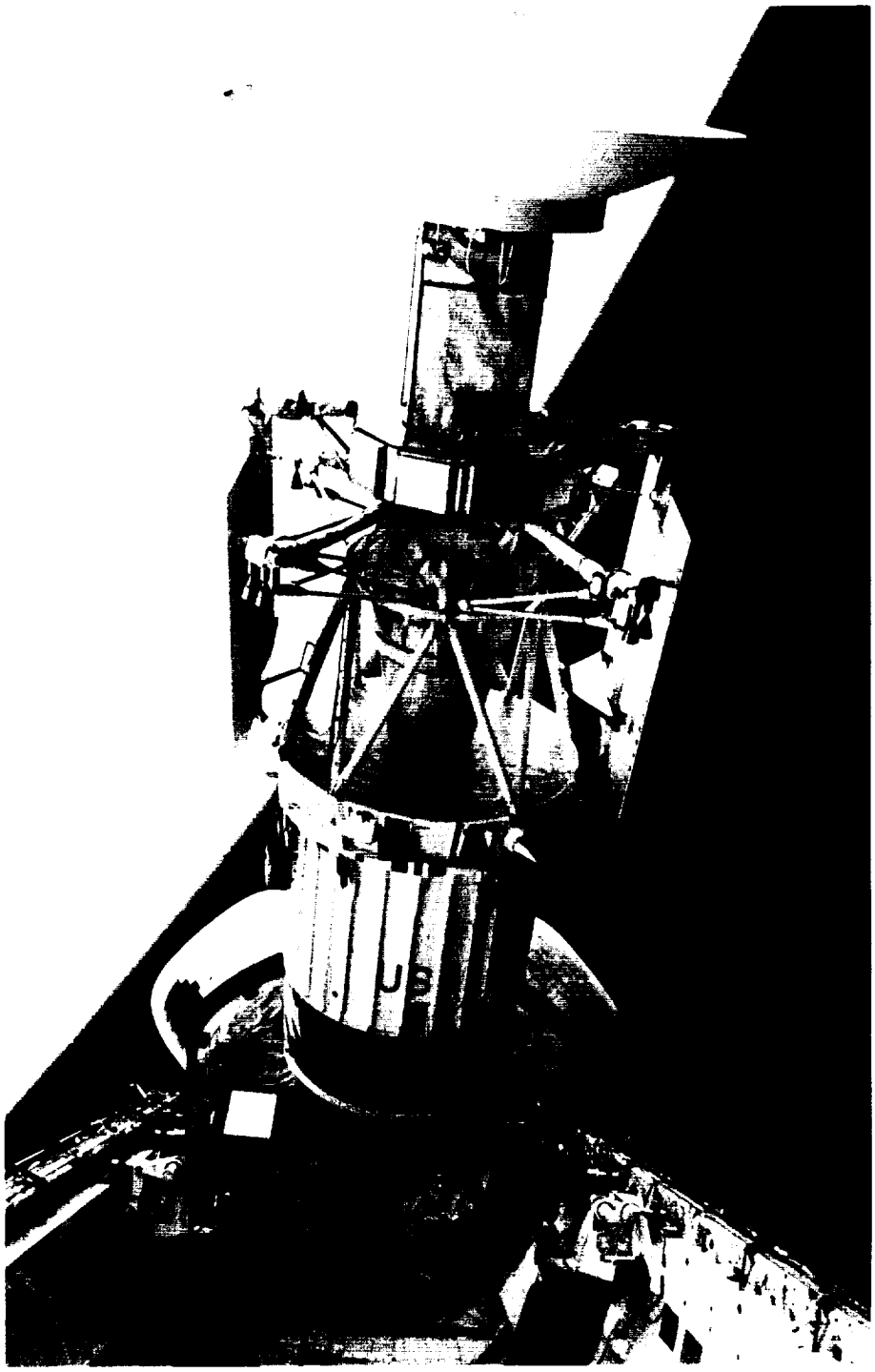

Figure 9-3. After five revolutions around the Earth, Magellan and its IUS booster were deployed from the shuttle.

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Figure 9-4. Magellan's solar panels were extended prior to IUS ignition because the booster's roll-control thrusters were too close to the ends of the panels in their stowed position.

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However, the positions of Earth and Venus during the late-April to late-May 1989 launch period required a Type-IV trajectory (see Figure 9-5). This meant that the spacecraft would travel between 1-1/2 to 2 times around the Sun (slightly more than 540 degrees) and that it would arrive at Venus on August 10, 1990. While it dictated a longer cruise duration (15 months), the Type IV actually had the advantages of reductions in launch energy and Venus approach speed.

Since launch, Magellan has traveled more than 1-1/2 times around the Sun at an average speed of 113,600 kilometers per hour (71,000 miles per hour) relative to the Sun and has logged over 1.261 billion kilometers (788 million miles). Three trajectory-correction maneuvers (TCMs) have kept the spacecraft on track for the correct aim point and arrival time at Venus. The TCMs were executed on May 21, 1989, and on March 13 and July 25, 1990.

Back to the Drawing Board

Magellan's Type-IV trajectory and the resultant Venus arrival date brought about some changes in the basic mapping plan developed for the 1988 mission.

Superior conjunction (where the Sun is positioned between Venus and the Earth) will now occur during the primary mapping mission, instead of at the end. The result is that up to 18 days of mapping data will be lost around November 2, 1990, because radio interference from the Sun will make it impossible to communicate with the spacecraft. Fortunately, the missing data can be recovered in early July 1991, if the mission is extended for additional 243-day mapping cycles.

The trajectory also dictates an approach over the north pole; this will result in a mapping swath from north to south, the reverse of that planned for the 1988 mission.

Cruise Activities

The word "cruise" conjures images of leisure, spare time, and relaxation. It is true that people who work on interplanetary missions usually take some time after launch to reflect on what it has taken to get that far

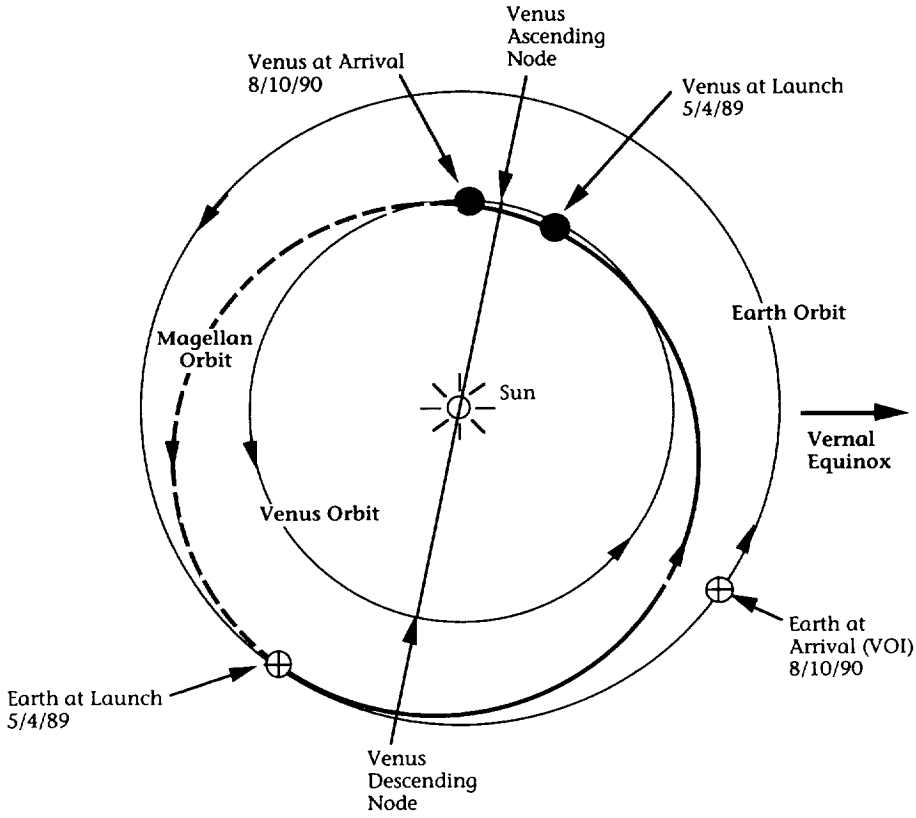

Figure 9-5. The spacecraft's trajectory is tilted slightly to the plane of the paper. The view is from the north ecliptic pole, with the trajectory shown as a solid line when it is above the page, and as a dashed line when it is below the page. Magellan will approach Venus from above the page, i.e., over the north pole.

and on what lies ahead to ensure a successful mission. But it's the "what lies ahead" that makes this period of reflection indeed brief.

Magellan team members have been occupied with two primary tasks during the cruise to Venus. The first was to fly the spacecraft and evaluate the performance of its various subsystems and components in the actual space environment. Ground test chambers are the next best thing to being there, but they cannot completely simulate interplanetary conditions. The second task was to plan and prepare for the activities that will occur in Venus orbit.

Getting to Know the In-Flight Spacecraft

The cruise period has not been a time of leisure for the spacecraft either.

Magellan has traveled farther from the Sun than Earth's orbit (149,669,000 kilometers or 93,000,000 miles) and has approached to within 104,640,000 kilometers (65,400,000 miles) of the Sun, 2,880,000 kilometers (1,800,000 miles) closer to the Sun than the orbit of Venus. This changing environment allowed us to characterize the thermal responses of various parts of the spacecraft over a range of temperatures as these parts faced toward or away from the Sun. Knowing these responses is referred to by spacecraft engineers as "having a model." The ability to refine and validate the thermal model means that we will be better able to predict the thermal response of the spacecraft once it is in Venus orbit.

Similarly, the spacecraft power models, both for input from the solar arrays and output from the batteries, were validated as we performed cruise activities that required varying power output.

A series of "guide-star" calibrations was carried out during cruise to determine precisely how the star scanner responds to the set of stars we plan to use for accurate spacecraft pointing during the prime mapping mission. These calibrations are called STARCALs.

Magellan is a three-axis-stabilized craft that relies on three reaction wheels to provide attitude (pointing) control (see Chapter 4). Four gyroscopes provide the information required to determine the attitude. Because extremely high pointing accuracy is required to successfully capture radar reflections from the planet's surface, several calibrations were conducted on the gyroscopes to provide a thorough understanding of their orientation and behavior.

Two types of gyroscope calibrations were conducted to correct two possible error sources. The Scale Factor Calibration (SFCAL) allows correction of the difference between the amount the spacecraft thinks it has turned and the amount it has actually turned in a large-angle excursion. The Attitude Reference Unit Calibration (ARUCAL) allows correction of the offset of the axes of the gyroscope assembly relative to

the star scanner reference frame. During flight, this offset can change from the amount measured before launch.

Pointing of the HGA was calibrated to assure its accuracy while performing the dual functions of radar mapping and telecommunications. This activity is called an HGACAL.

Another high-precision task was determining the desired orbit and its timing. Useful SAR images can be obtained only if the exact range from the spacecraft to the planet's surface is known throughout each mapping pass. Because Magellan's orbit will be highly elliptical, the range to the surface will change every moment and require frequent adjustments to the radar commands. Accurate calculation of the needed adjustments is totally dependent on precise knowledge of the orbit.

The orbit-determination task relies on a navigation technique called "differenced Doppler," which involves measurements of the spacecraft's signal using tracking antennas at the Spain and California (and sometimes the Australia and California) Deep Space Network (DSN) complexes. Obtaining these measurements during cruise refined the techniques, verified the procedures to be used in orbit, and assured us that the differenced Doppler approach will provide sufficient orbit-prediction accuracy to guarantee good radar-data collection.

Other major ground test activities that involved interaction with the spacecraft were the Mapping Readiness Tests carried out at the DSN sites; these tests verified that the DSN is primed to support mapping operations. Magellan will send 1.8 gigabits of data back to Earth during every orbit. Because the data will be stored on tape recorders during each mapping pass and overwritten with new data during the next pass, there will be only one chance during each orbit to send the data to a DSN station. Additionally, the timeline allows the station only one minute to lock on the spacecraft's signal before the data flow begins. The DSN's lockup and recording operations must occur without a hitch to avoid gaps in the Magellan Venus map. Results of the Mapping Readiness Tests verified that lockup can occur within one minute and validated the operational procedures for capturing all of the data from the spacecraft.

In December 1989, the radar electronics were turned on for the first time since before launch. Both the radar system and the hardware passed muster. This test paved the way for a more complicated test performed in May 1990, when the radar and the spacecraft were put through their paces for more than three days. The spacecraft turned through the intricate series of maneuvers it will perform orbit after orbit as it maps the planet. At the same time, the radar system issued its complex series of mapping commands. This period of simulated mapping operations allowed us to verify many spacecraft and ground procedures and much of the mapping software that will drive Magellan once it is in orbit around Venus.

Magellan has also performed some routine "housekeeping" activities. Star scans were performed daily to allow correction for the normal drift in spacecraft pointing, and the reaction wheels were desaturated twice daily to eliminate the momentum accumulated from small torques to the spacecraft caused by the Sun's radiation. These two activities are discussed in more detail in Chapter 4.

Planning for Orbital Operations

Familiarity with the spacecraft's in-flight characteristics gained during the first few months following launch allowed us to take a critical look at our plans for both the in-orbit checkout (IOC) and mapping phases and revise them where needed.

In-orbit checkout, a thorough examination of the spacecraft and the radar, will be the first event after achieving Venus orbit. Final planning for this activity took almost a year. Assembling the requirements for in-orbit tests, resolving conflicts between requirements, negotiating a fundamental plan, and working out the operational and procedural details was an intense effort conducted in parallel with the activities involved in flying the spacecraft.

Final planning for the primary mapping mission was also achieved during this period. The prime mission involves three distinct types of geometry: nonocculted mapping, the superior conjunction phase, and the apoapsis occultation phase. Each type places different constraints on the mapping plan, and each was analyzed and updated separately.

The results of the planning efforts for IOC and mapping are described in Chapters 10 and 11, respectively.

Practice Makes Perfect

Placing a spacecraft into a precise orbit around a planet millions of miles away, checking out its equipment and subsystems to make sure they are working properly, and pronouncing the spacecraft ready for mapping operations are responsibilities and pressures definitely a cut above those we face on a daily basis. But the Magellan team will perform this scenario throughout the VOI maneuver and the IOC phase. As with any well-orchestrated production, an intensive period of rehearsal has been essential.

The eight-member Mission Engineering Team has devoted a portion of the cruise period to developing and conducting operational readiness tests and various training exercises, including simulated anomalies, that have tested and evaluated our performance in carrying out the major mission functions mentioned above. These dress rehearsals allowed us to refine our procedures and techniques as we went through the actual processes and interfaces (some of which are complex and time critical) that will be required. Now we feel we are ready for the real thing.

Now's the day and now's the hour.

— Robert Burns

Chapter 10
In Orbit at Last!

The period from TCM-3 on July 25 to Venus arrival on August 10 includes a tightly linked sequence of activities. Results of the TCM maneuver led to updating the precise timing and attitude of the SRM ignition to optimize the burn that will insert Magellan into the desired orbit.

Venus Orbit Insertion

When the spacecraft is approximately 13 hours away from Venus, the pull of the planet's gravity will gradually increase the spacecraft's velocity relative to the planet from 15,984 kilometers per hour (9,990 miles per hour) to 38,944 kilometers per hour (24,340 miles per hour). At approximately 9:30 a.m. (Pacific daylight time) on August 10, 1990, the trajectory will bring Magellan over the north pole of Venus (see Figure 10-1). As the spacecraft dives toward periapsis at 10°N latitude, it will disappear behind the planet. Three minutes later, the SRM will ignite and begin its 84-second burn, braking Magellan to a speed of 29,600 kilometers per hour (18,500 miles per hour) relative to Venus. Once slowed, the spacecraft will be captured by Venus' gravitational field and transferred into a highly elliptical orbit around the planet.

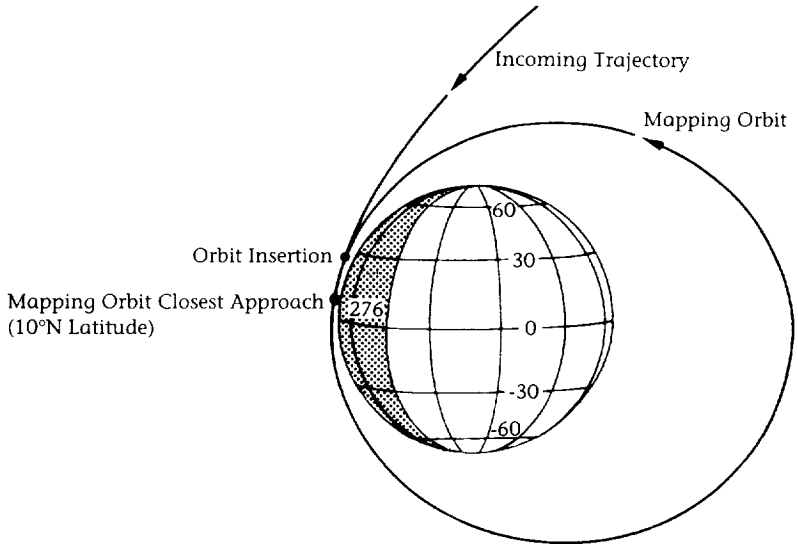

Figure 10-1. Magellan incoming trajectory at Venus.

Ground controllers would prefer the lines of communication to be open between them and the spacecraft during such a critical event. However, the SRM burn and VOI maneuver will take place "behind" the planet, as viewed from Earth (see Figure 10-2), thus preventing communication until the spacecraft emerges some 30 minutes later.

The shuttle/IUS launch combination allowed Magellan to carry only one SRM. As it approaches Venus, the spacecraft will be traveling too fast to achieve a circular orbit (which is ideal for radar mapping) from the deceleration provided by the single SRM burn. The planet will therefore be mapped from an orbit that is highly elliptical.

In-Orbit Checkout

Before jumping into 8 months of full-time mapping operations, the mission-critical activities of the IOC phase will be conducted over a period of 22 days, from August 10 through August 31.

The first item on the agenda is reconfiguration of the spacecraft from an interplanetary cruiser to a planetary orbiter. This involves separating the spacecraft from the SRM and allowing it to drift away. The separation is accomplished by firing four pyrotechnic separation nuts and allowing springs to push apart the spacecraft from the SRM at a slow

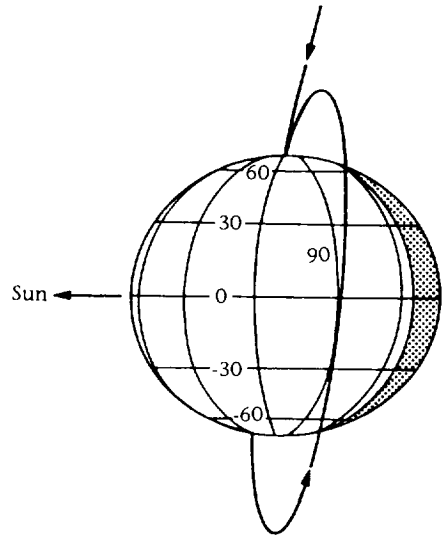

Figure 10-2. Magellan incoming trajectory at Venus as viewed from Earth.

rate of only 0.9 meters per second (2.6 feet per second). The spacecraft's reconfiguration also requires changing the fault-protection logic from that which is appropriate for cruise to that which is suitable for orbital operations.

It takes several days to generate the first set of commands for IOC activities; the generation of these commands follows the collection of navigation tracking data that tell ground operations personnel what orbit the spacecraft actually achieved. It is important to acquire good orbit data prior to starting IOC operations, because the success of so many of the IOC activities requires that the orbit be accurately determined.

The first set of sequences will include a series of commands to the spacecraft to point the HGA at Earth, increase the telemetry rate from 40 to 1,200 bits per second, and play back the data recorded during the VOI burn. These data will allow Magellan navigators to reconstruct

Did you know . . .

The maximum force that Magellan will experience from the 17,000-pound thrust of the SRM burn for the VOI maneuver is seven times the force of Earth's gravity.

the orbit-insertion event and assist them in designing the orbit-trim maneuver (OTM) scheduled for August 28. If, at that time, the spacecraft is already in the targeted orbit, the OTM will be deleted from the sequences and mapping operations will begin August 29. If the OTM is required, mapping operations will begin September 1.

Calibrations conducted during cruise indicate the offset between the onboard gyroscopes and the star scanner reference frame. Any change in offset between the HGA and the star scanner, resulting from the shock of the VOI burn, will be determined by performing a HGACAL on August 19. This calibration involves passing the signal from the HGA back and forth across a DSN receiving station immediately after the spacecraft performs a star calibration.

Did You Know . . .

It took the shuttle's three main engines and two SRMs, the two IUS SRMs, and one orbit-insertion SRM to put Magellan into orbit about Venus. Over 99 percent of Magellan's trip, however, has been an unpowered ride through space.

Four health and calibration tests of the radar system will be conducted during IOC. (Note that the nonsequential numbering of the tests resulted from changes in plans that included a decision to not reuse any numbers that were associated with discontinued tests.)

Radar Test 1 (August 15) is a stepwise power-up of the various components of the radar subsystem, which leaves the radar in the standby mode. From this point onward, the plan is to never turn off the radar.

Test 2.5 (August 16) presents the first opportunity to collect radar reflections from the planet. The radar will be operated in a mode whereby the timing commands will be changed in a very coarse manner so that fundamental timing calibrations can be performed. As a result, Test 2.5 will not provide full swaths (or strips) of data, but rather a number of "framelets" down the length of the mapping passes.

Test 3 (August 22) will provide the first full-length strips of data. This test will use the look-angle profile that will be used for the mapping phase, as well as radar-control commands that vary continuously as orbit altitude and look angle change through the mapping pass. The data from Test 3 should provide strips that can be mosaicked into the first large image.

While Test-3 data are being analyzed, Test 5 will be performed August 24. This test is intended to measure the performance envelope of the SAR by testing combinations of look angle and radar-timing commands that should push the limits of the ground software to process the data into images. While this test is not expected to produce data for the final Magellan Venus map, it will provide invaluable information to support data interpretation.

Several "Recovery Days" (August 14, 21, and 29) have been scheduled in case anomalous conditions occur. In such a situation, the plan would be to correct the anomaly and resume the preplanned IOC schedule. The recovery days would give ground personnel a chance to accomplish that goal. Alternatively, they would provide ground personnel with some welcome breathing space if IOC proceeds as planned.

At the end of IOC, the spacecraft should be in the targeted mapping orbit, the parameters of which are given in Table 10-1. The orbit is nearly fixed inertially in space (i.e., Venus will rotate under the spacecraft) and will not precess appreciably over the length of the 243-day mapping cycle.

Now it's time to start collecting data for the Magellan Venus map.

Table 10-1. The Magellan mapping orbit

Parameter	Value
Periapsis altitude, kilometers (miles)	257 (172)
Apoapsis altitude, kilometers (miles)	8,000 (5,000)
Periapsis latitude	10°N
Orbit period, hours	3.15
Inclination (relative to Venus' equator), degrees	85.3

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

— T. S. Eliot

Chapter 11
Mapping the Veiled Planet

About one hour after passing through apoapsis, Magellan will turn its large parabolic antenna away from Earth and aim it down at Venus off to the left of the spacecraft's direction of motion, in preparation for the start of the mapping pass. As the radar begins operation at an altitude of 2,150 kilometers (1,350 miles) over the north pole, the data will be stored on two onboard tape recorders. As the altitude decreases, the spacecraft will turn so that the look angle (HGA angle from nadir) increases to improve the range (cross-track) resolution of the radar images. After moving through periapsis at 10°N latitude, Magellan will begin its long climb toward apoapsis. As the spacecraft rises, the look angle will be reduced to preserve signal strength sufficient for good-quality imaging and to counteract the increasing distance from the planet. When the spacecraft passes an altitude of 2,400 kilometers (1,500 miles), the tape recorders will be full and the radar will be put in the standby mode.

After the spacecraft turns to point its antenna toward Earth for DSN lockup, half the data will be transmitted for the next 56 minutes. The data playback will be interrupted for 14 minutes while the spacecraft rotates off Earth-point to perform a star scan. Another rotation back to Earth-point and DSN lockup will be followed by an additional 57 min-

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utes of data transmission. The spacecraft will then begin its way back down to Venus, and the entire process will be repeated.

A total of 1,852 data-collection and playback passes (see Figure 11-1) will occur during the 243-day mapping cycle.

Each mapping pass will image a swath of the planet about 25 kilometers (16 miles) wide by about 16,000 kilometers (10,000 miles) long. Since the spacecraft's orbit remains essentially fixed in inertial space, the slow rotation of Venus continually brings new areas into view under the spacecraft. Swath overlap will vary, but averages around 5 kilometers (3 miles). The 243-day mapping cycle will cover a full 360 degrees of Venus longitude. Nearly 90 percent of the surface of Venus can be mapped during the mapping cycle, if all goes well; the rest can be mapped later if there is an extended mission that provides additional mapping cycles.

The Mechanics of the Mapping Pass

Because of the orbit inclination, the HGA must point to the left (with respect to the spacecraft's direction of motion) as it crosses over the north pole. Thus the mapping cycle is performed with the spacecraft in a left-looking configuration.

Because of this orientation, the south pole cannot be mapped until and unless the Project is funded for additional 243-day mapping cycles, even if there were enough data-playback time in each orbit to map a full 180 degrees in latitude (which there is not). To map the south pole, the spacecraft will have to be rotated 180 degrees and operated in a right-looking configuration.

Figure 11-2 shows the geometry of the orbit, Venus, the Sun, and Earth every 25 days from VOI through the 243-day mapping cycle. The location of superior conjunction is also shown in Figure 11-2 as the bold line following the point of VOI +75 days.

Several of the major geologic regions in Venus' northern hemisphere are shown in Figure 11-3. The slow, retrograde rotation of the planet can be seen as the major features (Beta Regio, Ishtar Terra, and Aphrodite Terra) move as a function of days past VOI.

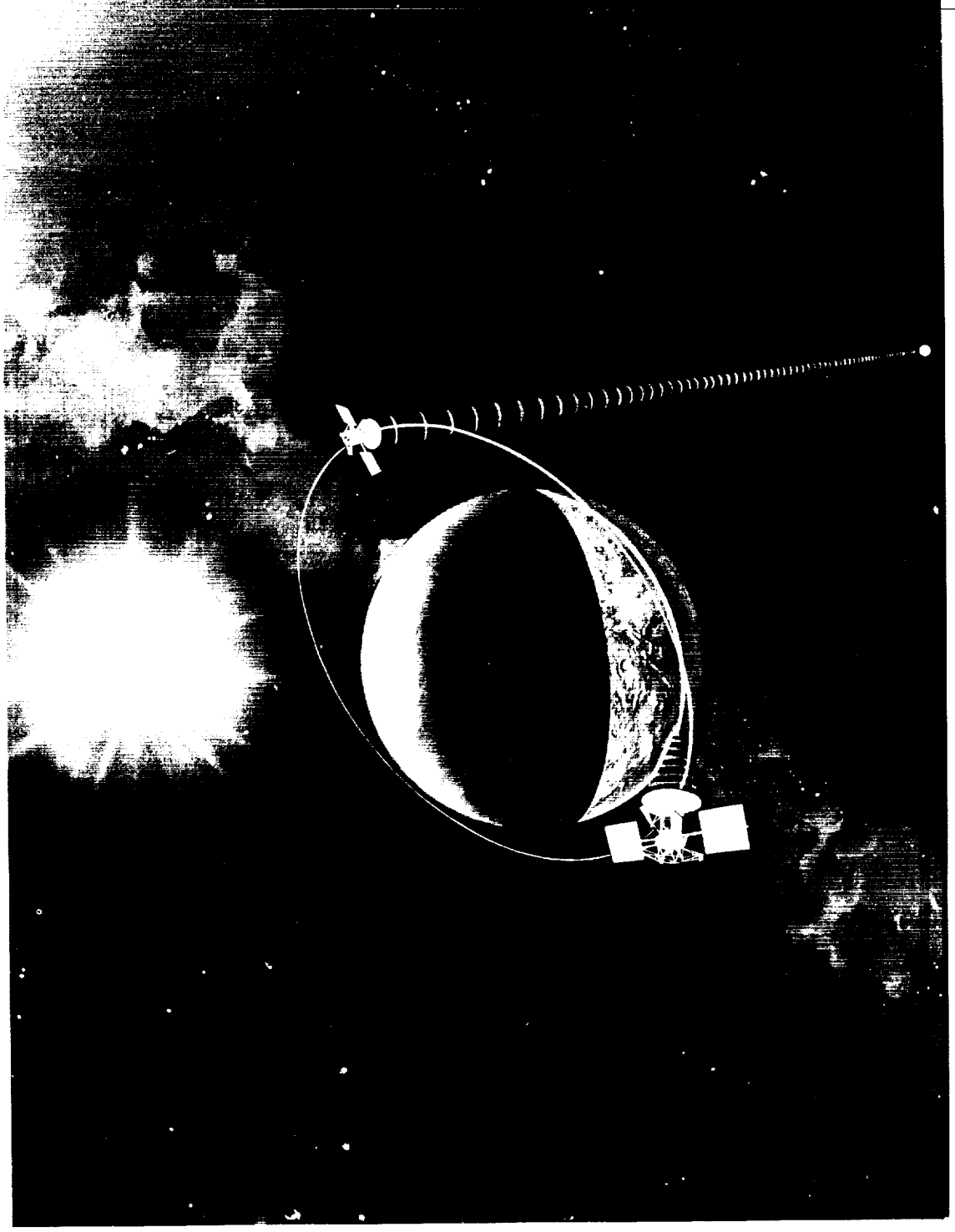

Figure 11-1. When Magellan's elliptical orbit brings the spacecraft close to the Venusian surface, the radar instrument will "look" through the clouds to map the solid planet. Magellan will spend most of the rest of its orbit transmitting data back to Earth.

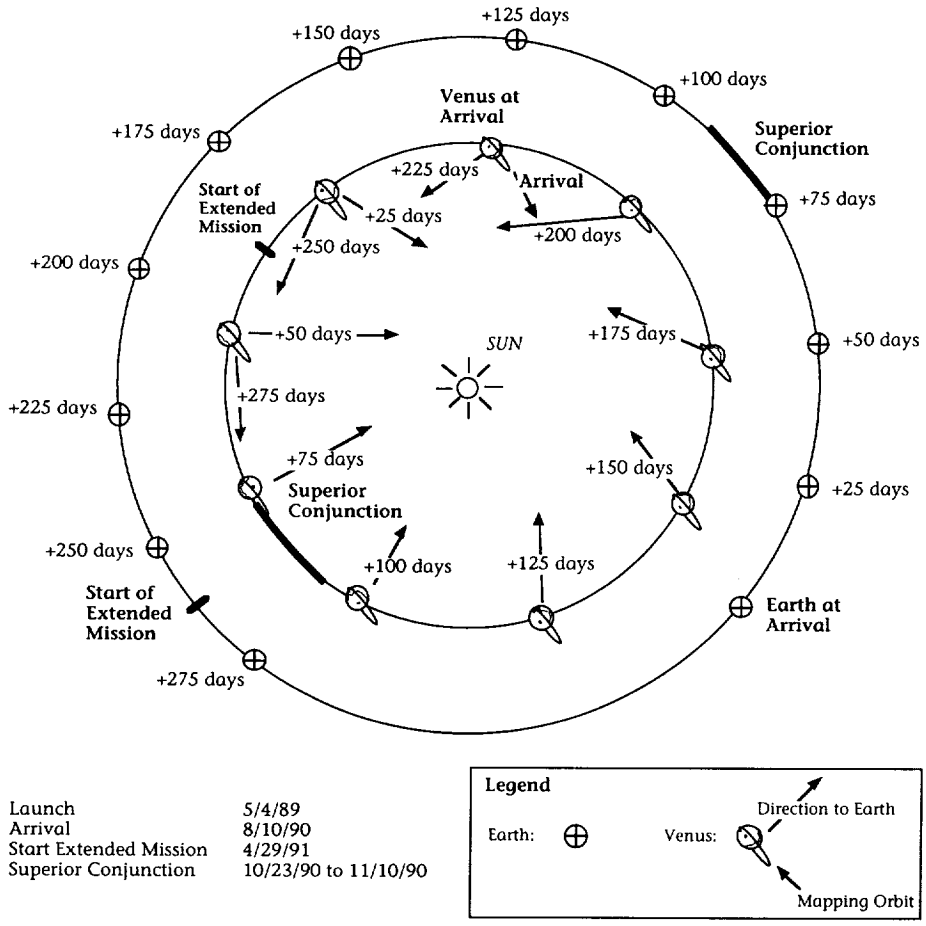

Figure 11-2. This view from the north pole of the solar system shows the geometry of the Magellan orbit.

As mentioned in Chapter 9, the 243-day mapping cycle can be divided into several distinct phases during which spacecraft operations are conducted in slightly different ways. These phases are driven by geometry considerations involving the positions of the Sun, Venus, Earth, and the spacecraft's mapping orbit.

The simplest geometry occurs when there is a clear line of sight between the spacecraft and a DSN receiving station during data playback. The mapping operations conducted in this phase are referred to as "nominal," or "nonocculted." The plans for nominal mapping form the baseline from which alterations will be made to meet the special geometric needs of possible extended mission cycles.

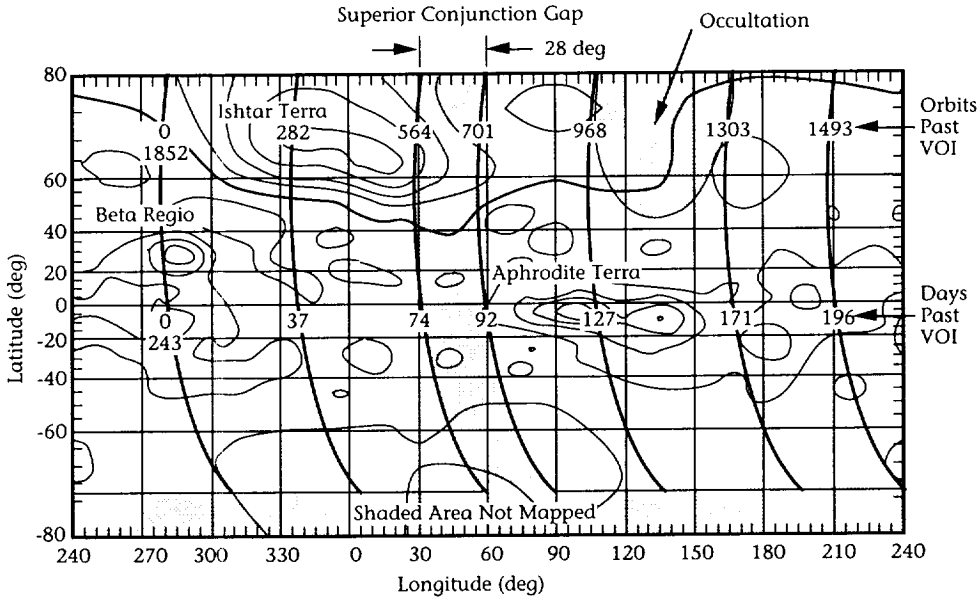

Figure 11-3. Venus mapping coverage.

In nominal mapping, the 3.15-hour orbit period is divided as shown in Figure 11-4. An "alternating swath" strategy is used to maximize coverage of the planet. Although Venus rotates the same number of degrees at all latitudes during each orbit, the number of square miles of new terrain under the spacecraft is much greater near the equator than near the poles. This makes it possible to map the high latitudes on every other orbit and still obtain a good margin of data overlap between swaths. The lower latitudes, however, need to be mapped every orbit to avoid holes in the final Magellan Venus map. The alternating-swath mapping strategy thus reduces redundant data collection in the northern polar region and allows collection of data farther south than would otherwise be possible.

Using this strategy, the spacecraft alternates between mapping from the north pole down to 56.9°S latitude on one orbit (an "immediate" swath), to mapping from 66.9°N latitude down to 74.2°S latitude on the next orbit (a "delayed" swath). Mapping orbits are thus either "immediate" or "delayed."

Each record (data-acquisition) period, whether for immediate or delayed swaths, is 37.2 minutes long and fills the onboard tape recorders

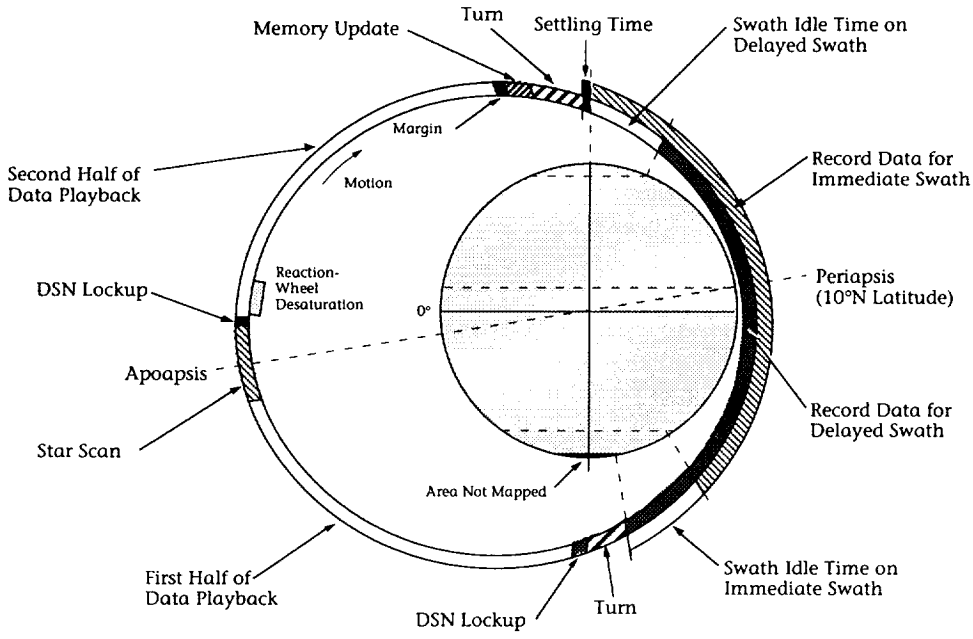

Figure 11-4. Mapping orbit profile. The spacecraft moves in a clockwise direction to perform the distinct phases of the mapping pass.

(called the Data Management Subsystem [DMS]). The tape recorders must be emptied every orbit because they will be refilled with data from the next orbit.

Figure 11-4 also shows the two playback periods that occur during every orbit. The playback rate is 268.8 kilobits per second, which is only one-third the record rate of the radar data. For this reason, the total playback period is three times that of the record period and takes up the bulk of time during each orbit. The playback period is divided into two parts to allow time for a star scan to maintain spacecraft pointing accuracy.

Table 11-1 lists the major mapping events and their time allocations. If the orbit period achieved at VOI is less than 3.15 hours (189 minutes), but not short enough to require an OTM, the time allotments for mapping events will be adjusted. Maximum mapping coverage is the goal and serves as the guideline for any timing adjustments.

During that phase of the prime mission when the Sun is very nearly between the Earth and Venus (approximately 18 days centered on

Table 11-1. Mapping Orbit Time Allocations

Event	Duration, minutes
Turn to mapping	5.7
Settling time	0.5
Record mapping	37.2
Swath idle time	7.5
Turn to play back	5.3
DSN lockup	2.5
First playback	56.6
Star scan	14.0
Second playback	57.2
Memory update	2.0
Margin	0.5
Total	189.0

November 2, 1990), the superior conjunction mapping plan will be used. Concerns that constrain planning for superior conjunction are twofold.

(1) When the line of sight between the spacecraft and Earth passes close to the Sun, command signals sent to the spacecraft and data returned from it can be corrupted by interference from the solar plasma. The amount of interference experienced depends greatly on the level of solar activity at the time the signal passes the Sun, either outbound to the spacecraft or inbound to Earth.

(2) If a hardware or software fault occurs while the spacecraft is executing complex operations (like mapping), it may not be possible for ground controllers to get enough data to diagnose the problem or send commands to the spacecraft successfully.

The mission plan for the superior conjunction phase, therefore, calls for us to stop mapping altogether from October 31 through November 5, 1990. Mapping operations will continue until October 31 only if the Sun is "quiet." During this period, we will try to get engineering telemetry from the spacecraft for one work shift per day.

We will study the quality of the telemetry throughout the conjunction period and will resume mapping as soon as it is safe to do so. If nature smiles on us, no more than 7 to 10 days of mapping data will be lost during this period.

The occulted mapping phase (December 16, 1990, to January 26, 1991) will find Venus between the spacecraft and Earth for part of the playback portion of the orbit. During this phase, the record duration will be reduced and the mapping parts of the orbit shifted to reduce the amount of playback time required to the precise amount geometrically available. Magellan science investigators expressed a preference for obtaining coverage at the southern extreme of the mapping pass during this phase, since this area will be "new" terrain. Therefore, the start of the 44-minute mapping pass will be delayed during this phase, with the amount of delay determined by the maximum length of the occultation during the period covered by the stored sequence on the spacecraft. This will put a "hole" in the Magellan Venus map in the northern latitudes, also shown in Figure 11-3.

Did you know . . .

Magellan will travel 61,302 kilometers (38,314 miles) around Venus during each orbit at an average speed of 19,461 kilometers per hour (12,163 miles per hour).

The Magellan prime mission is that period between the end of IOC and April 29, 1991, approximately the time it takes Venus to rotate once beneath the spacecraft's orbit. If we are able to start collecting map-quality data 19 days after VOI (i.e., only if things go well in IOC and no OTM is needed), we will be able to "close the map" by the end of the prime mission. If an OTM is needed, or if map-quality data are not collected until sometime after mapping operations have begun (nominally September 1), several days of mapping past the nominal end of the prime mission will be required.

Alternate Mission Strategies

Because spaceflight operations rarely proceed without a hitch, several alternate mapping strategies have been developed. In general, contin-

gency planning is best accomplished in cool, collected moments, not in the heat of an emergency. With that in mind, we have planned ahead for a dozen or so categories of problems that could change the way mapping data are collected from the time of the failure forward (see Table 11-2).

Since the spacecraft is built to be single-fault tolerant, most single failures allow the automatic substitution of a backup component for the failed one, and operations can recover the original mapping strategy with very little lost time or data. More complex failures, however, require preplanning to avoid excessive lost time in replanning at the time of the emergency.

Even so, there is no guarantee that quick contingency planning will not be required at some point in the mission—nature often finds a way to break those things we are least prepared to have broken. Development of a number of plans ahead of time, however, has always proven to shorten the time required to replan strategy following an actual failure, even if the failure is one for which no plans have been made.

Table 11-2. Categories of Problems Requiring Alternate Mission Strategies

Shortened mapping swath required.
High solar activity.
Star scans fail frequently.
Thermal problems.
Low voltage during mapping.
High bit-error rate (uplink and/or downlink).
Tape recorder problems.
SRM does not separate from spacecraft.
Reaction-wheel failure.
Inability to use X-band uplink.
Major radar- and/or altimeter-antenna failure.
Major gaps in DSN tracking coverage.
Interruption of mapping to perform spacecraft calibrations or tests.
Fault-isolation plan for separating spacecraft pointing errors from radar-system problems.

Extended Mission

An extended mission to recover data missed during the first 243-day mapping phase (Cycle 1) and to conduct the high-resolution gravity experiment is a vital part of achieving all of the science objectives of the Magellan mission.

Preliminary preparation for the first extended mission cycle (Cycle 2) was conducted during the cruise period. The final planning for Cycle 2 and the preliminary work for subsequent cycles will be addressed during Cycle 1 (prime mission) operations.

Extended mission science objectives were developed in collaboration with the Magellan science investigators. Those objectives are divided among several mission cycles, as follows.

Cycle 2 primarily involves radar mapping. Its main objective is to fill in all large coverage gaps left from Cycle 1. These gaps will be of three kinds: those that were geometrically impossible to obtain during Cycle 1 (i.e., those during superior conjunction and apoapsis occultation, and those of the south pole), those that may have occurred because of DSN coverage losses from any delay in "start up" at the end of IOC and the beginning of mapping, or those from any problems encountered during Cycle 1 that resulted in data loss.

The focus on radar data in Cycle 2 is due partly to the importance of obtaining a complete map of Venus to support geological interpretation of the planet and also to the geometric impossibility of proceeding to the high-resolution gravity experiment until late in Cycle 2 (the last 32 days). It may well be that the gravity experiment will begin in the last month of Cycle 2.

The high-resolution gravity experiment requires pointing the spacecraft's HGA at Earth during periapsis. When Venus is between the spacecraft and Earth during this part of the orbit, the gravity experiment cannot be performed. Only during the times when periapsis is not occulted can this part of Magellan's mission objectives be met.

Conducting the gravity experiment is the prime objective in Cycles 3 and 4; the fill-in of any remaining SAR coverage gaps will take place on a time-available basis.

Hear ye not the hum of mighty workings?

— John Keats

Chapter 12
Getting the Job Done

When you think about the Magellan mission, you might be inclined to focus on the marvels of the spacecraft and the radar, on the thrill of finally unveiling some of the mysteries of Venus, or on the fact that it's wonderful to be alive during this historic period of solar-system exploration.

But you might not think about people, plans, and coordination. This chapter encourages you to do so, for it's about the people of Magellan and how they get the job done.

Planning and Coordination

The Magellan scientists have met for many years on a quarterly basis to plan the mapping coverage requirements that will best meet the scientific objectives of the mission, to participate in key decisions about the radar system, to help lay out data-processing procedures, and to decide how the data can best be presented for study and public release. Since most of the scientists are not employed at JPL, their interests in these activities are represented within the Project by the five members of the Mission Operations Science Support Team.

The scientists have sharpened their skills in interpreting radar images by participation in workshops and in field trips to sites that

provide a direct comparison of geologic features with SAR images of the areas visited.

Most of the Magellan scientists will be in residence at JPL at various times throughout the 8-month mapping cycle. The Science Mission Support Area on the second floor of Building 230 has been equipped with sliding display boards, light tables, and sufficient flat surfaces to accommodate large mosaics and maps. Offices for the various science disciplines contain computer workstations that will allow investigators to access, view, and manipulate the radar imaging data. All in all, the environment is conducive to image analysis and the exchange of ideas as the scientists strive to understand the newly acquired information about the geology and geophysics of Venus.

However, before the scientists can get their hands on the data, an enormous amount of planning will be carried out by the aptly named Mission Planning Team (MPT), whose nine members are located at JPL and Martin Marietta. A few of this team's tasks include planning major mission events such as launch, cruise, trajectory-correction maneuvers, spacecraft and/or radar-system tests and calibrations during cruise, Venus orbit insertion, and the activities of the in-orbit checkout phase.

Precision is the key word when describing the activities of the 12-member Navigation Team (NAV). Working in close concert with the MPT, the Magellan navigators provide precise information on the spacecraft's location as it travels to Venus, on how much rocket thrust will accomplish a needed trajectory-correction maneuver, and on the precise location of the spacecraft as it approaches the planet and is readied for orbit insertion.

The activities of Magellan's Ground Data System (GDS) Office extend to just about every element within the Project. Based on the unique needs of the various Project teams, the 85 members of the GDS develop, test, upgrade, and maintain the automated tools required for the team functions. Nearly every activity mentioned in this chapter has been affected by the efforts of the largest team within the Project.

Instructing the Spacecraft

Although Magellan is a highly sophisticated robot, it depends on ground personnel to tell it precisely what to do and when to do it. Since it is not practical to send instructions to the spacecraft every day, and because Magellan is equipped with its own internal clock, a set of commands covering a period of several weeks during cruise (one week during mapping) is sent to its computer a few days before the command sequence begins. Several teams within the Project work together to build the sequence of spacecraft and radar-instrument commands. Coordination and cooperation are the key elements in this process.

Creation of the Mission Plan marks the beginning of sequence development. The Plan and an associated Mission Profile (a graphic chart that shows the desired activities and approximately when they are to occur) are developed by the Mission Planning Team, based on inputs from other teams within the Project. For example, inputs from the Spacecraft Team (SCT) specify certain activities necessary to operate the spacecraft. Since the mapping activities will be of a repetitive nature, the inputs to the sequencing process will typically cover a 4-week period or four stored sequences.

When the final inputs are ready, they pass to the Mission Sequence Design Team (MSDT), whose 12 members are located at JPL and Martin Marietta. This team builds a baseline sequence, which is a minutely detailed timeline of the desired activities. A typical sequence will span 8 days of activities or 61 orbits around Venus, and includes an extra day that is planned not to be used. (Incidentally, a complete, printed timeline can span over 5 meters [17 feet] in length.) The MSDT task includes resolving conflicts among specific events and figuring out how much antenna tracking coverage is required for the activities. This detailed timeline lays the groundwork needed by the SCT to develop engineering sequences that will execute the desired activities.

The SCT, whose 68 members are resident at JPL and Martin Marietta, is responsible for the health and optimal use of the spacecraft. Through continuous analysis of engineering telemetry, the SCT monitors the status of Magellan. In addition to developing sequences into the final command load that will be sent to the spacecraft, the SCT ensures that

the instructions do not violate spacecraft operating constraints and that they will fit into the spacecraft's computer memory.

The 17-member Radar System Engineering Team (RSET) from the Hughes Aircraft Company, but in residence at JPL, monitors the health and performance of the radar sensor, develops the detailed instructions for its operation, and ensures that commands to the sensor do not violate spacecraft and/or sensor operating constraints.

Once the final command load is built and verified and has received approval by the Mission Director, a final step by the SCT converts the load from a text file to the stream of bits (1s and 0s) that will be sent to the spacecraft.

Throughout the building of a command load, the five-member Mission Operations and Command Assurance Team provides independent checks of the overall quality of the commanding process and suggests improvement where needed.

The sequence design process, from handoff of the mission planning input through transmission to the spacecraft, takes approximately 6 weeks of technical interaction, give and take, teamwork, reviews, and decisions.

Flight Operations

The Mission Control Team (MCT) of about 20 members located at JPL is the real operator of the spacecraft. In addition to controlling all transmissions to the spacecraft, the MCT receives all telemetry at JPL from the spacecraft. It monitors real-time spacecraft performance and verifies the proper execution of transmitted sequences.

A particularly important task of the MCT is scheduling the resources that provide the path of communication to and from the spacecraft. This activity begins months in advance of the requested coverage dates and involves coordination of Magellan requirements with operational organizations outside the Project, such as the DSN, JPL's Multimission Control and Computing Center (MCCC), and the NASA/Goddard Space Flight Center's NASCOM communications network. These resources are essential for certain spacecraft activities and yet they must be shared with other flight projects such as Galileo, Voyager, and Pioneer. With

such a demand for DSN services, it's no wonder that the scheduling process is indeed involved.

Representatives of the MCT, other flight projects, and the DSN regularly meet to negotiate equitable allocations of antenna tracking support. The amount of tracking time acquired by a project is dependent on the relative importance of that period to its mission. For example, Magellan will receive simultaneous coverage from two tracking antennas during the critical Venus orbit-insertion maneuver on August 10, and will have continuous tracking coverage during the 243-day mapping phase of the mission.

More About the Deep Space Network

The continuous 24-hour tracking of several spacecraft requires Earth-based antenna sites at strategic locations that compensate for the Earth's daily rotation. The Deep Space Communications Complexes (DSCCs) in Spain, Australia, and California are approximately 120 degrees apart in longitude, which ensures continuous observation and suitable overlap time for transferring the spacecraft radio link from one site to the next.

The Australian DSCC is located 40 kilometers (25 miles) southwest of Canberra near the Tidbinbilla Nature Reserve. The Spanish site is 60 kilometers (37 miles) west of Madrid at Robledo de Chavela. The Goldstone complex resides on the U.S. Army's Fort Irwin Military Reservation, about 72 kilometers (45 miles) northwest of Barstow, California. The international staff required to operate the DSN numbers over 1,100 people.

The Network Operations Control Center (NOCC), which controls and monitors operations at the three DSCCs, is located at JPL. The Network's Ground Communications Facility (GCF) at JPL provides and manages the communications circuits that link the complexes, the NOCC, and the various remote flight project operations centers at JPL.

Each DSCC consists of four deep-space stations equipped with ultra-sensitive receiving systems and large parabolic dish antennas (see Figure 12-1). There are two 34-meter- (111-foot-) diameter antennas, one 26-meter- (85-foot-) diameter antenna, and one 70-meter- (230-foot-) diameter antenna. The 70-meter antennas at all three DSCCs were extended

Figure 12-1. This 70-meter- (230-foot-) diameter antenna, which is almost as large as a football field, is located at the Deep Space Communications Complex in Australia.

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from their original 64-meter (210-foot) diameters to increase their sensitivity in preparation for the Voyager 2 spacecraft encounter with Neptune in August 1989.

The high data rate (268.8 kilobits per second) and the precise navigation requirements associated with Magellan's mapping phase will impose a support load on the DSN as heavy as or heavier than any during the past 30 years. To meet this challenge, the DSN has implemented major modifications to its telemetry and navigation systems. Equally important is the operational support required during the mapping phase. To acquire all high-rate mapping telemetry and generate the requested navigational data during Magellan's 8-month mapping phase, the DSN will be required to provide, on a daily basis, approximately 36 hours of antenna and antenna-related support.

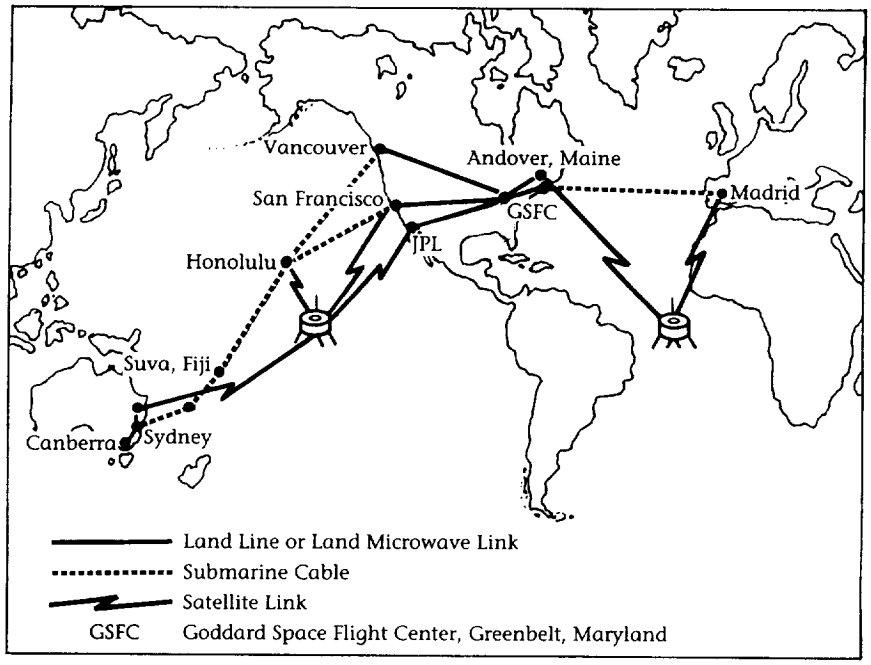
During this time, the DSN will also support Galileo, Ulysses (to be launched in October 1990), Voyagers 1 and 2, Pioneers 10 and 11, and the International Cometary Explorer (ICE). Magellan, Galileo, and Ulysses will be in their prime mission phases and will have the highest priority. However, the Pioneers, Voyagers, and ICE will continue to have well-defined scientific objectives. Even with a lower priority, they will have substantial "survival" requirements that must be met. In addition, a significant amount of time must be made available for Network maintenance and new-implementation test and training.

The DSN has estimated that Magellan support losses, depending on the date within the 243-day mapping phase, will be from zero to a maximum of 5 hours per day. Any losses will be the result of conflicts with other flight projects, but primarily those with the Galileo prime requirements and Pioneer 11 and ICE survival requirements. The overall impact of these losses on Magellan is relatively slight. The losses will be mostly evidenced in a reduction of station overlap time; therefore, continuous telemetry coverage will be essentially unaffected. Since the primary loss will be a reduction of some opportunities to acquire a certain type of navigation data, the DSN has developed an alternate Doppler data type that is expected to compensate for this loss.

Commanding

Once the sequence command load is ready and the communication resources are scheduled, command operations get under way.

The Operations Planning and Control Team (nine members) moves the command file (via magnetic tape) to the Magellan Command Subsystem at the MCCC, where the file is formatted to GCF standards. The GCF electronically transmits the command file to the appropriate DSCC via a combination of communications satellites and conventional surface and undersea circuits (see Figure 12-2). The DSN Operations Team at the DSCC checks the file for correct reception, removes the GCF formatting bits, and routes the file to the appropriate antenna for transmission to the spacecraft. Traveling at the speed of light, the first command will reach the spacecraft in 14 minutes; Magellan's acknowledgment of receipt will require another 14 minutes to reach ground engineers.



NOTE: Not shown are the satellite links between JPL and Denver, CO, and between JPL and Goldstone, CA.

Figure 12-2. Land-based telephone lines and microwave links, submarine cables, and communications satellite links of the Ground Communications Facility.

Receiving Data

The data received during Magellan's cruise and mapping phases are of enormous value. The telemetry includes engineering data that indicate the performance of the spacecraft and its subsystems. This information is identified with spacecraft time so that the state of the spacecraft at any given time can be completely reconstructed.

The navigation data collected during the cruise period indicate whether the spacecraft is on the right course for Venus. Mapping-phase navigation data will provide precise knowledge about Magellan's orbit, which will be used to adjust the radar commands for optimal use of the radar sensor.

The radar-mapping data in the telemetry results from playback of the tape recorders during each orbit. These data will eventually be processed into photo products for interpretation by Magellan scientists.

The Mapping-Phase Data Flow

As the data stream from Magellan arrives at the DSCC, it is recorded on magnetic tape. From this point on, the recorded data are called Original Data Records (ODRs). The radar imaging, altimetry, and radiometry ODRs, which include a certain amount of embedded engineering data, are shipped to JPL, since the high data volume exceeds the capacity of the electronic links.

Most of the engineering data are relayed electronically to JPL via the same combination of ground and satellite links mentioned earlier that provides the capability to uplink commands to the spacecraft. These data are received at JPL by the Space Flight Operations Center (SFOC), a new multimission control center that incorporates the latest data-handling and processing technology. The spacecraft engineering data and a sampling of radar engineering data are automatically checked at the SFOC to determine if the spacecraft and the radar are operating within predetermined safety bounds. The data are sorted into measurement types (i.e., spacecraft, navigation, radar engineering) and are made available to the appropriate Magellan teams through an SFOC database. The data are archived in the SFOC on computer-compatible

tape and will eventually be transferred to Magellan's Data Management and Archive Team (DMAT) for permanent retention.

Processing the Data

The radar imaging, altimetry, and radiometry ODRs shipped to JPL are received by DMAT and routed to SFOC, where the raw radar data are initially processed by the Magellan High-Rate Processor. The data are time-ordered and put into an internationally recognized standard format.

After the radar data are processed and returned to DMAT, they are in the form of an Experiment Data Record (EDR). The ODRs are also returned to DMAT for storage in an environmentally controlled vault, to be used again only if an EDR is lost or destroyed. (A more detailed discussion of the activities of DMAT appears later in this chapter.)

Did you know . . .

As a way of demonstrating progress in making the Magellan Venus map, a 1.8-meter- (6-foot-) diameter globe of Venus will be constructed. As Magellan images are received, they will be mosaicked and pasted onto the globe. The globe will be on public display at JPL during and after the mosaicking.

The imaging and radiometry EDRs are passed to the 14-member SAR Data Processing Team, where they are fed into the SAR Data Processing Subsystem (SDPS). The data, which were compressed on board the spacecraft to allow transmission, are expanded into the original format and, through a complex system of processing, made into an image strip.

The DMAT forwards the altimetry EDRs directly to the Image Data Processing Team (about 24 members), where both raw data processing and mosaicking are performed in the Image Data Processing Subsystem (IDPS) to produce large maps that show the height of surface features.

The image strips produced by the SDPS are also processed by the IDPS, which mosaics them into large area maps of Venus.

Data Products

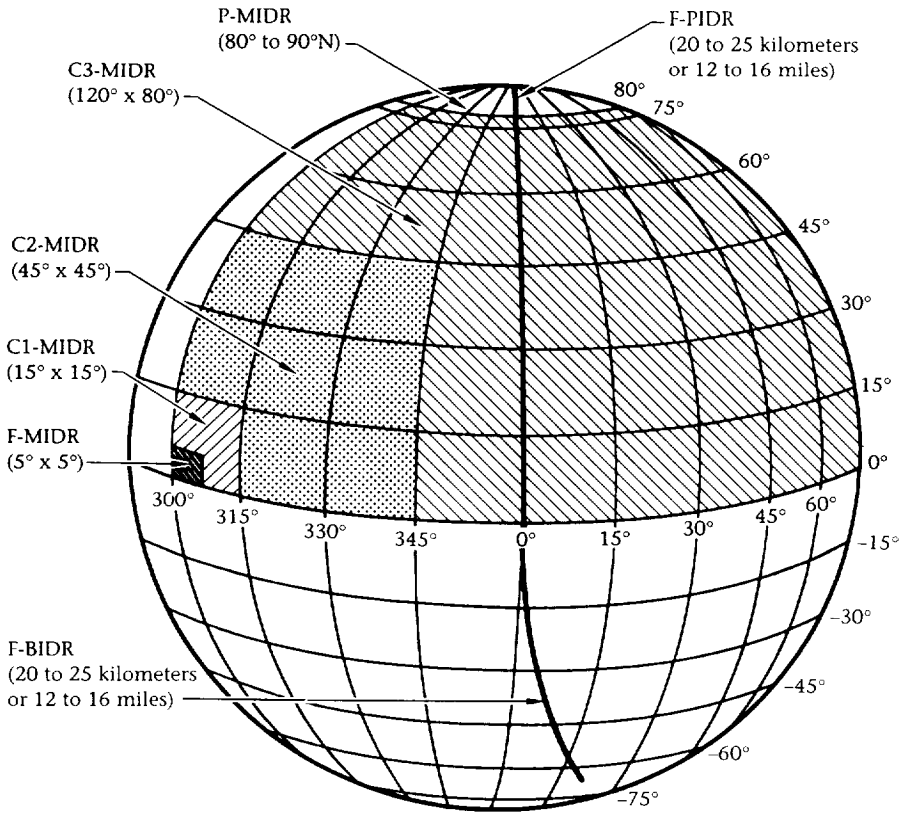
The primary image data product created from each orbit's data is the long, narrow image strip mentioned above, which represents a surface area about 25 kilometers (16 miles) wide by approximately 16,000 kilometers (10,000 miles) long. This strip, termed a Full-Resolution Basic Image Data Record (F-BIDR), is the basis for all the image products that will be used for study and interpretation. Some 1,852 such image strips will be produced during Magellan's 243-day mapping cycle.

However, the large volume and the unwieldy width-to-length ratios for these image strips make them unsuitable for general use. Thus, further processing will be done to produce mosaicked images (Mosaicked Image Data Records, or MIDRs) that can be more readily used for photo interpretation and comparison with the altimetry and radiometry data.

Generating full-resolution mosaics for the 90 percent of the planet covered by F-BIDRs would create an enormous data set, severely taxing available processing facilities and funds. To streamline processing and focus efforts toward the production of sets of mosaics that can be used for a variety of studies, a decision was made to compile and distribute global mosaics from F-BIDR data that have been compressed. The compressed strips are called C-BIDRs ("C" = compressed). Mosaics generated from the C-BIDRs are called C1-MIDRs (C1 = compressed once) and will have enhanced photo-interpretative attributes because of speckle reduction during the compressing process. The C1-MIDRs will also be used to generate another set of mosaics, the C2-MIDRs (compressed twice). Finally, the C2-MIDRs will be further compressed to produce the C3-MIDR data set. Thus, the resulting global mosaics from compressed data will provide views 15 by 15 degrees, 45 by 45 degrees, and 80 x 120 degrees, respectively. (The mosaics will not be evenly shaped; therefore, the above values are expressed in degrees for computational ease and because of the difficulty in placing odd-shaped mosaics on a sphere. However, 1 degree equals approximately 100 kilometers [62 miles].)

On the other hand, to ensure availability of the full-resolution data, approximately 15 percent of the F-BIDRs will be processed into full-resolution mosaics (F-MIDRs) for key regions on the planet's surface.

Twenty major data products will be produced from the radar data for use by the Magellan scientists. Figure 12-3 shows the planetary coverage for several of these products.



F-BIDR	Full-Resolution Basic Image Data Record
F-PIDR	Full-Resolution Polar Image Data Record
F-MIDR	Full-Resolution Mosaicked Image Data Record
C1-MIDR	Compressed-Once Mosaicked Image Data Record
C2-MIDR	Compressed-Twice Mosaicked Image Data Record
C3-MIDR	Compressed-Thrice Mosaicked Image Data Record
P-MIDR	Polar Mosaicked Image Data Record

Figure 12-3. The planetary coverage for several types of Magellan data products. Full-Resolution Polar Image Data Records (F-PIDRs), as well as mosaicked products (P-MIDRs), will be generated for the north polar region to help determine the actual pole location. (Note that F-BIDRs are not actually aligned with lines of longitude.)

All Data Roads Lead to DMAT

All Magellan data products will be under the care and control of the 20-member Data Management and Archive Team.

In support of Magellan mission operations and science-analysis efforts, DMAT will collect, catalog, disseminate, and archive data products generated during the mission's lifetime.

Included in the Magellan data set will be standard data products generated from the multiple-step processes described above, products generated by the Magellan science investigators at their home institutions, and a collection of mission operations support products.

All of these data products will reside in the DMAT area at JPL in a variety of formats: magnetic tapes, photographs, negatives, optical discs, maps, and hardcopy listings. The DMAT library will have computer workstations for accessing the DMAT database and drafting and light tables to aid in product analysis. All data products in the library will be available for temporary loan to authorized Project users.

Did you know . . .

The Magellan Data Management and Archive Team (DMAT) is unique. The activities of this team represent the first time that a spaceflight project at JPL has employed a single team to manage and archive a complete set of project data products.

Additionally, DMAT will maintain a separate, environmentally controlled facility that will house an archival set of data products, including raw telemetry, engineering analysis, uplink, and navigational products. At the end of the Project, this data set will be transferred to the Planetary Data System (PDS) and to the National Space Science Data Center (NSSDC), NASA's long-term archiving and analysis facilities.

Prior to the end-of-Project transfer, DMAT expects to manage approximately 100,000 products, including both the working and the archive sets. A somewhat staggering 300 data products will flow through DMAT on a daily basis alone. About 25,000 more products (tapes, photo products, optical discs, and computer discs with read-only

memories [CD-ROMs]) will be produced and distributed to investigator home institutions. Many of these products will also be provided to NASA's worldwide Regional Planetary Image Facilities.

The DMAT will provide yet another dimension to the interface with the Magellan science investigators: comparative analysis support. The focus of this activity is on scientists' requirements for data about the Earth and other planets for comparative analyses of Venus. Acting primarily as an information resource, this effort involves the collection, organization, maintenance, and cataloging of photo products, publications, maps, and other kinds of non-Magellan data.

Through all of these efforts, DMAT will assure that all of the acquired data will be available and accessible for current and future analysis, and that it will be preserved as an historical record of the Magellan mission.

Believe Us, There Is More

The activities discussed in this chapter were necessarily presented in an extremely streamlined fashion that does not begin to tell the whole story of the inner workings of the Magellan Project. Countless reams of paper document the specific responsibilities of the various Project teams and their intricate and sometimes complex interfaces within and outside the Project.

All of the teams mentioned above are noted on the Project's organization chart in Chapter 13. Also shown on that chart are additional functions not covered in this chapter, although they are nonetheless important to the overall operation of the Project. As you look at the organization chart, we urge you to give a special nod to those positions and people who carry out the Project's managerial, financial, procurement, administrative, and secretarial efforts. They provide the adhesive that holds it all together.

The right people in the right jobs.

— Otto von Bismarck

Chapter 13
Project Organization

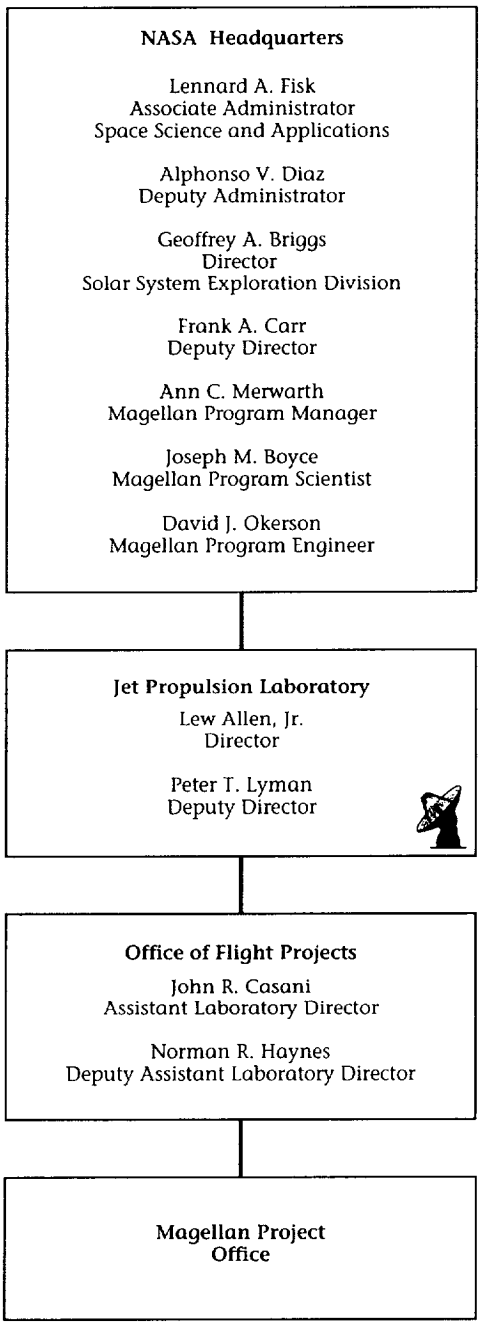
The Magellan Team

This chapter acknowledges the more than 300 current members of the Magellan team, whose names appear in Table 13-1. Most are employed at JPL, with the exception of the science investigators and two groups of individuals who perform their Magellan assignments at the Martin Marietta Astronautics Group in Denver, Colorado, and the Hughes Aircraft Company in El Segundo, California.

The Magellan team is not autonomous and depends for its success on the contributions of other personnel within the JPL/Caltech family, at NASA Headquarters and other NASA centers, and at the three antenna sites of the Deep Space Network. Because all spaceflight projects necessarily span several years, from the early conceptual stage through project end, many members of the team have completed their particular contributions and gone on to other assignments, or have retired.

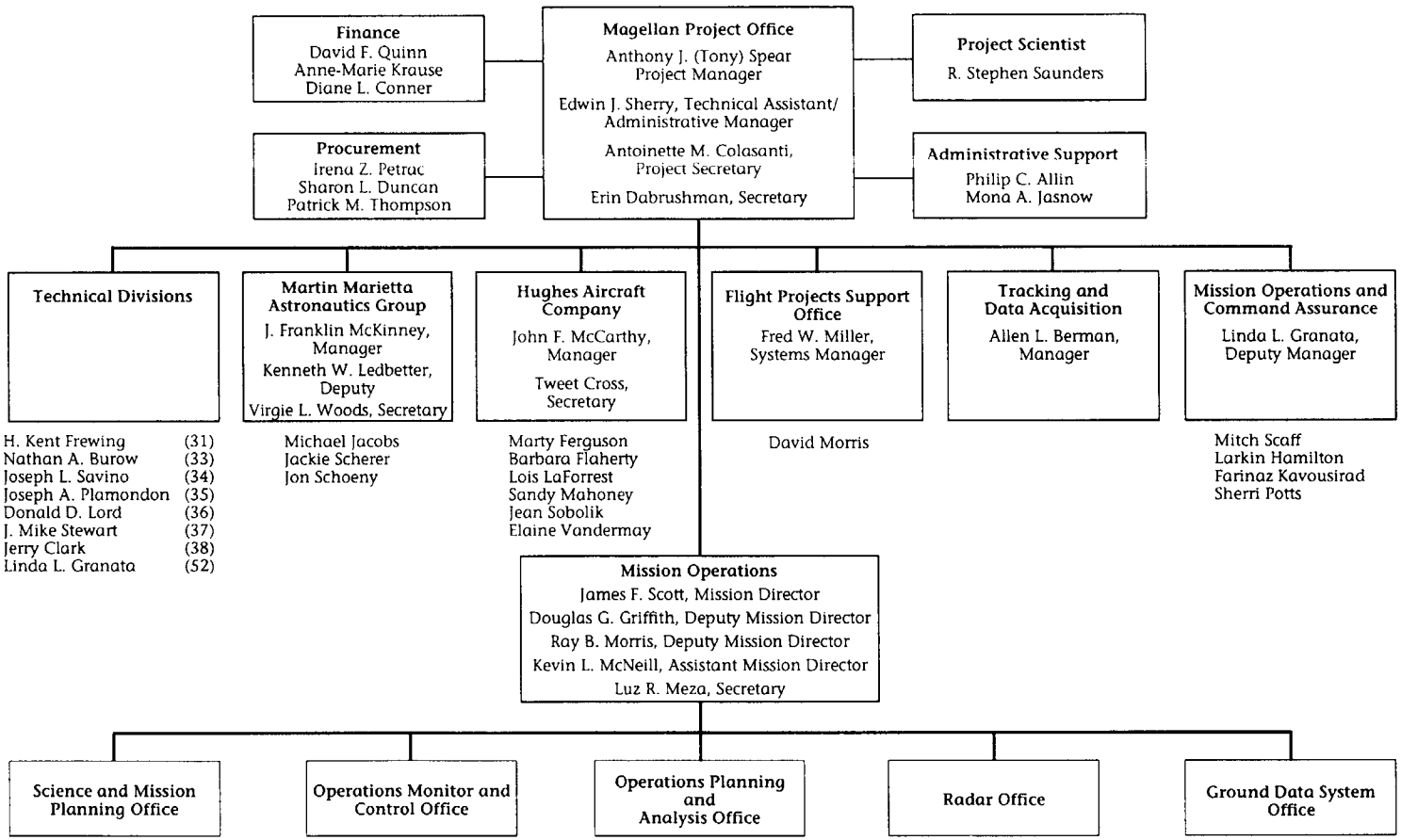
Therefore, the salute extended here recognizes not only current team members but also encompasses a larger group that brought Magellan to the eve of Venus arrival and to a continuing realization of its mission objectives.

Table 13-1. Magellan Project Organization



DSN personnel at Goldstone, California; Canberra, Australia; and Madrid, Spain.

Table 13-1. Continued



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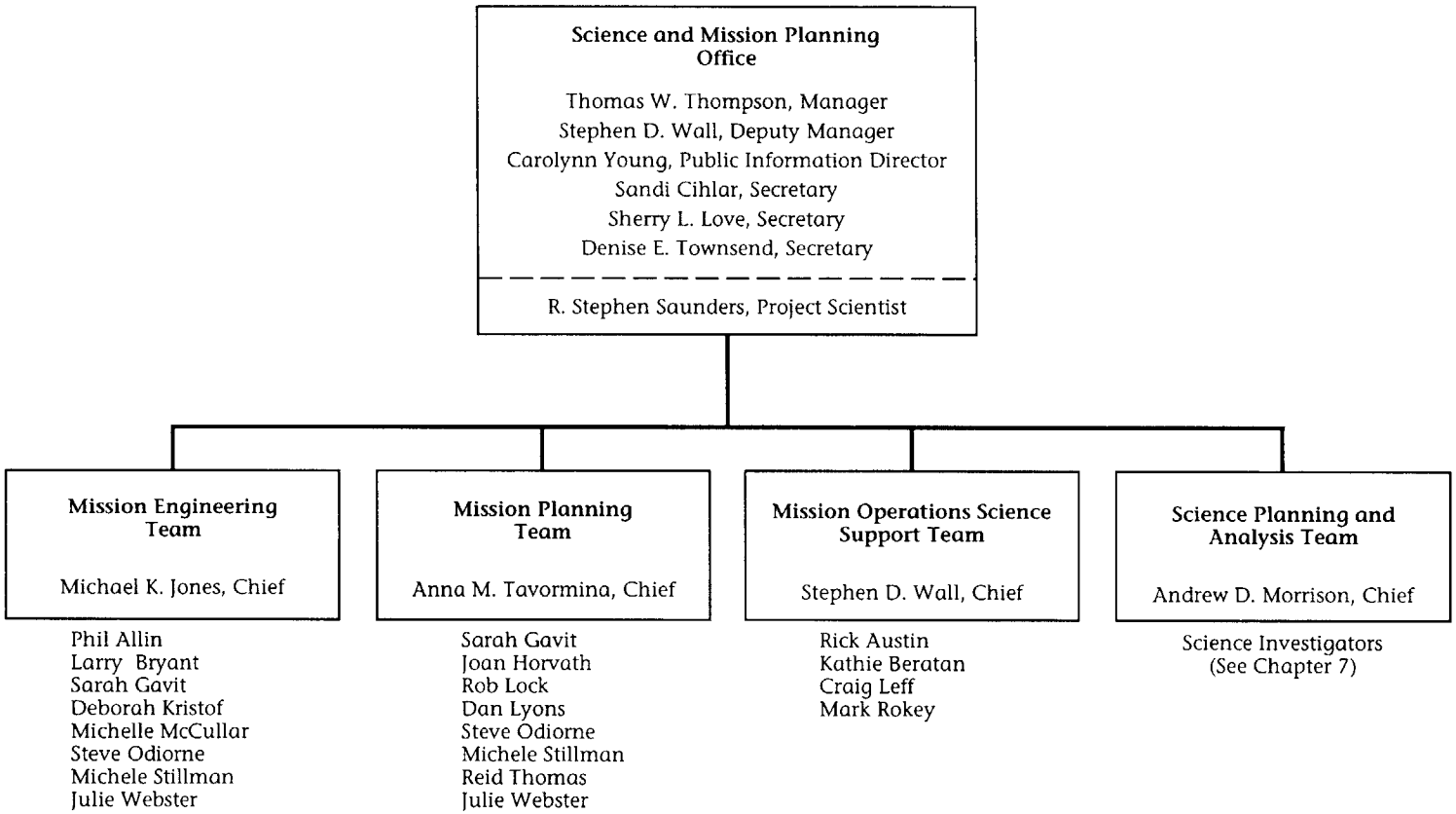

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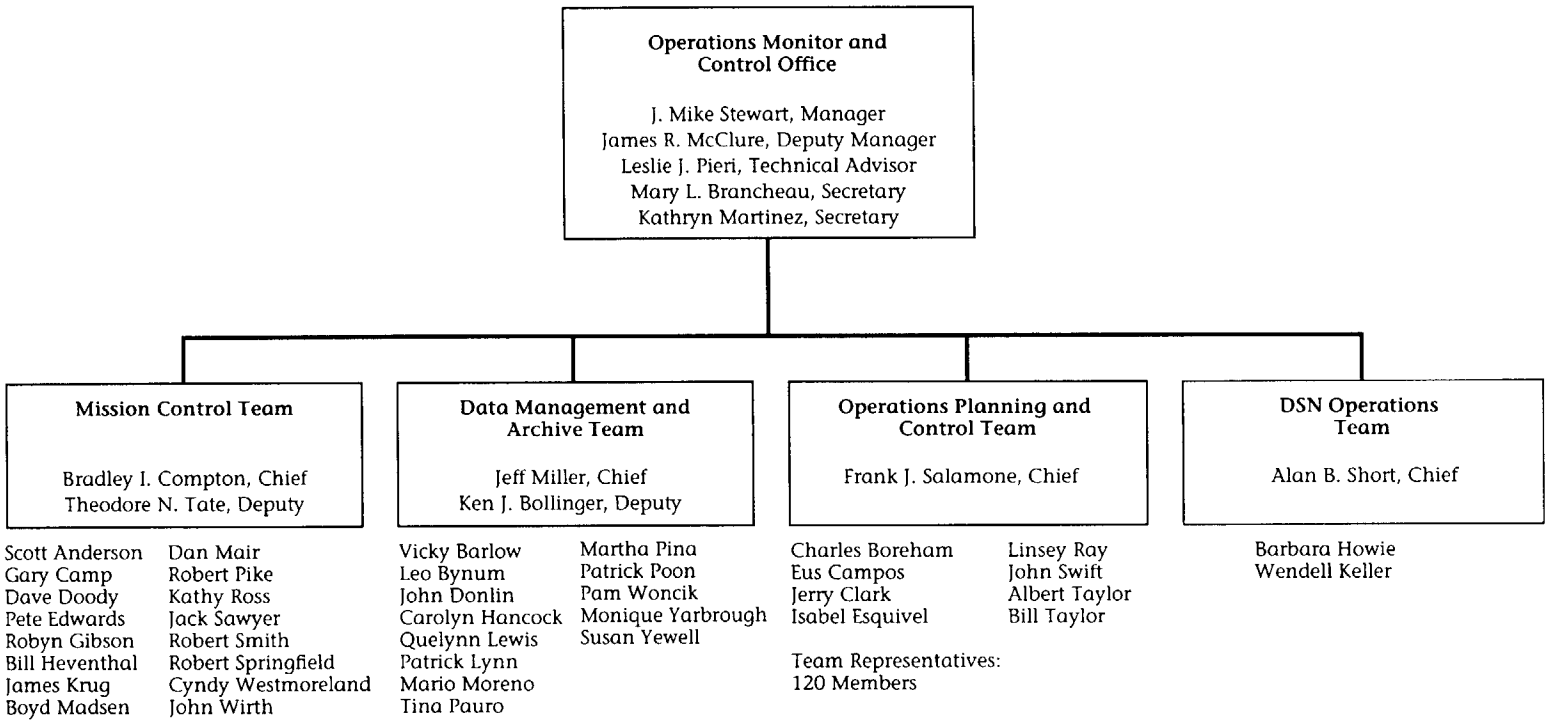

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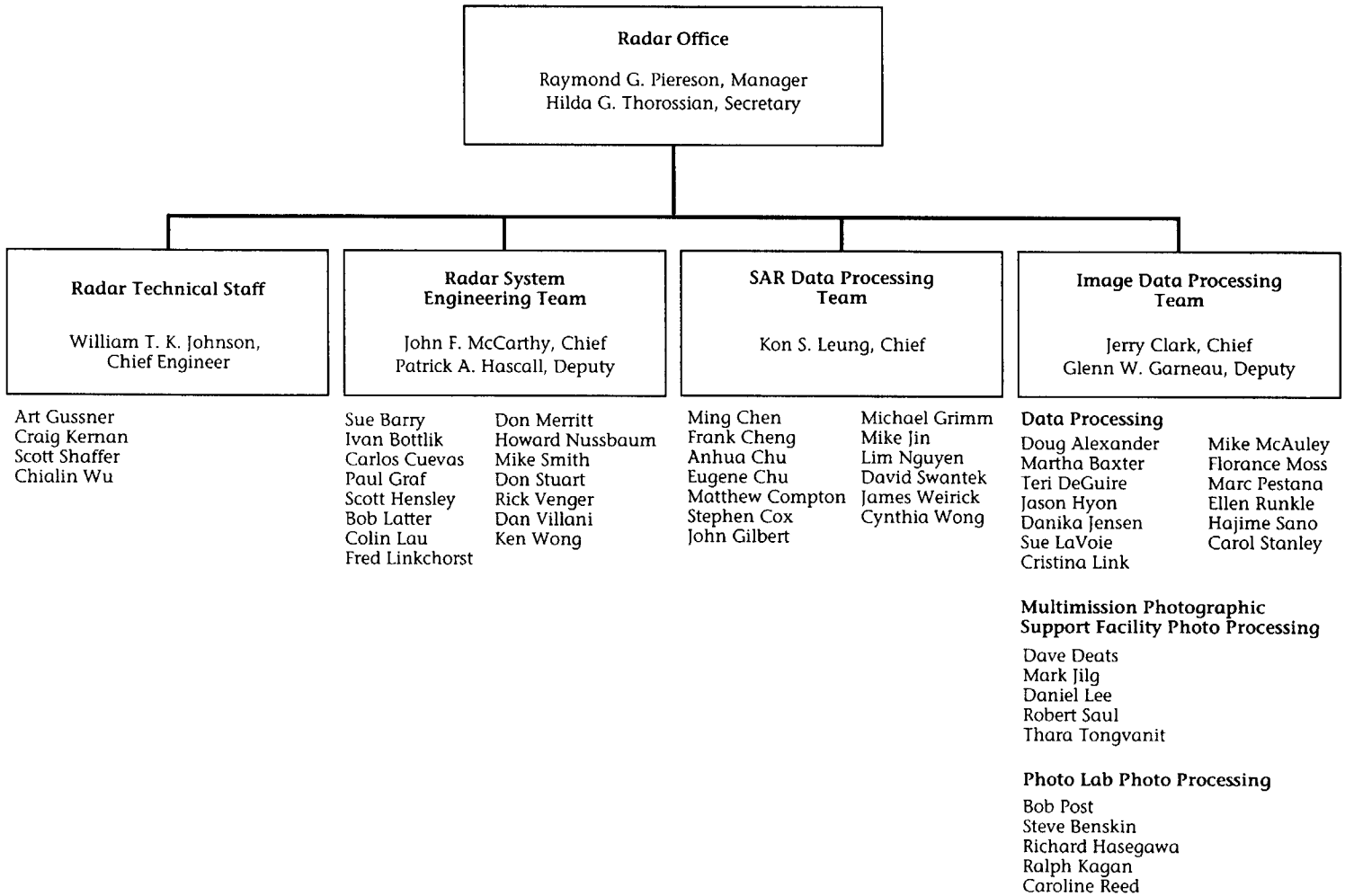

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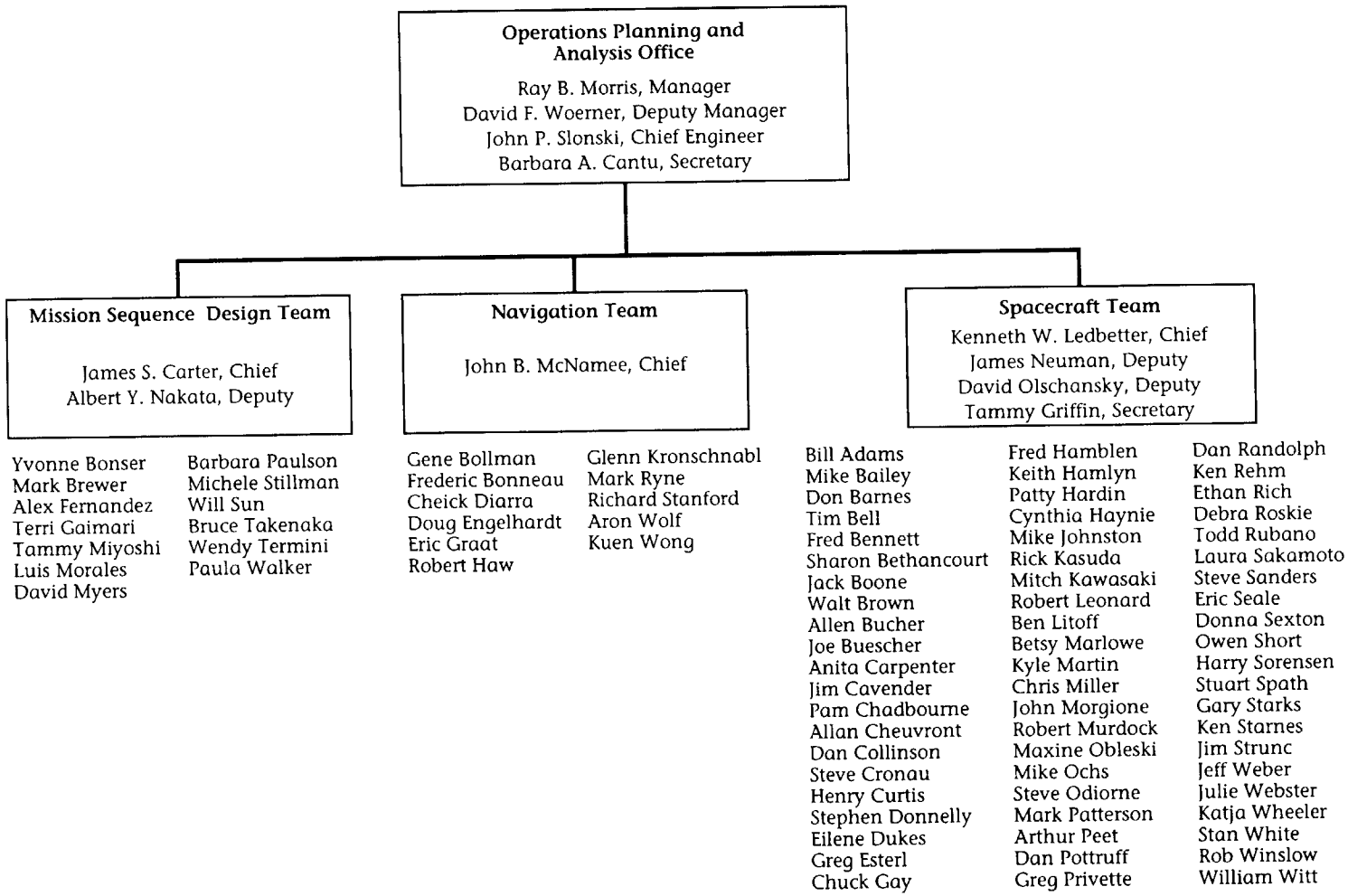

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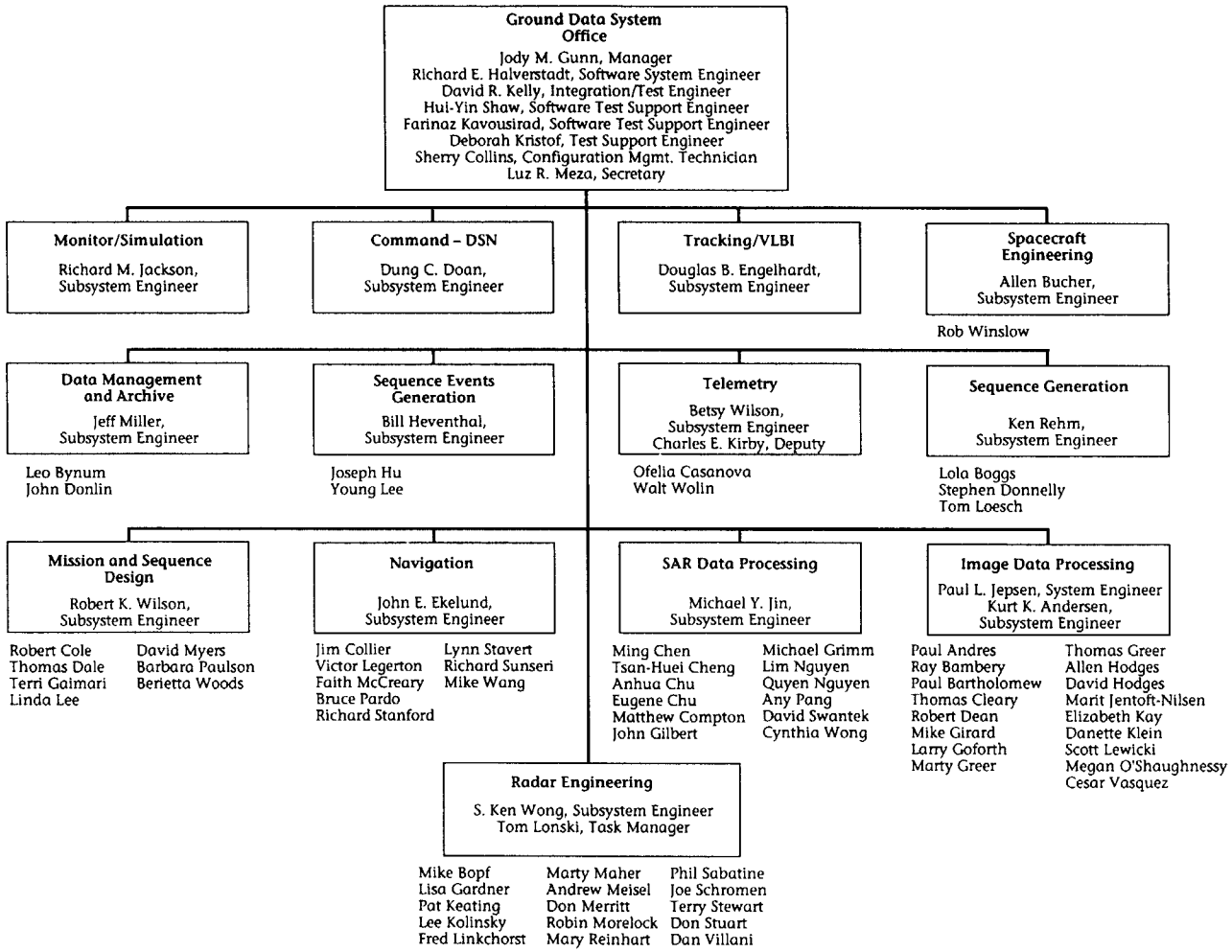

The Magellan Review Board

Additional members of the Magellan team compose the Magellan Review Board. Established in accordance with JPL policy and practices, the Review Board acts in an advisory capacity to aid the Project Manager in those critical decisions that affect the performance, schedule, costs, and other commitments of the Project.

Unless otherwise noted, Review Board members are employees of JPL.

Magellan Review Board

E. Kane Casani (Chairman)
Raymond J. Amorose
Glenn E. Cunningham
John H. Gerpheide (Special Consultant)
Norman R. Haynes
Richard L. Horttor
Chris P. Jones
James F. (Frank) Jordan, Jr.
Terry D. (Dave) Linick
Robert Marcellini (Lockheed Corporation)
James Martin (Ex-Officio, Consultant)
Ann Merwarth (NASA Headquarters)
David Newlands (Hughes Aircraft Company)
Ronald A. Ploszaj
Albert R. Schallenmuller (Martin Marietta Corporation)
William S. Shipley
Robertson Stevens

I dipt into the future as far as human eye could see,
Saw the vision of the world and all the wonder that would be.

— Alfred Tennyson

Chapter 14
Coming Attractions

Since the space age began in 1957, NASA/JPL spacecraft have visited every planet in the solar system except Pluto. Although these past missions have rewarded us with extraordinary glimpses of the other worlds orbiting the Sun, in many cases what we have collected is precisely that—glimpses. To understand better what these missions have shown us or hinted at, we must go back with other spacecraft.

Consider the most unforgettable moments of the Voyager Project, as it unlocked mysteries at Jupiter, Saturn, Uranus, and Neptune. During the past 12 years, we have been astonished by erupting volcanoes on Jupiter's moon Io and complex, colorful eddies in the Jovian atmosphere; organic compounds at Saturn's moon Titan and the haunting beauty of the braids in Saturn's rings; the rugged geography of the Uranian moon Miranda, and the geysers on the Neptunian moon Triton. As gratifying as all these experiences were, they were achieved while our spacecraft were flashing by at incredible speeds. They all point to many other questions that we would like to answer by returning for another, more thorough, look.

The same is true of other planets in the solar system. Revisit missions are in the works for Jupiter and Saturn. Project Galileo—launched in October 1989—will place a heavily instrumented probe into Jupiter's

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atmosphere and a capable spacecraft in orbit about the planet; both accomplishments will be firsts at this body. The Cassini mission to Saturn has similar goals, except a probe will be dropped into the thick atmosphere of Saturn's moon Titan, with hopes that it will reach that body's unseen surface.

Planets are not the only targets of upcoming missions at JPL. One spacecraft, Comet Rendezvous Asteroid Flyby, or CRAF, will expand on the "snapshot" data of international missions to Comet Halley in 1986 by meeting and accompanying Comet Kopff for more than three years. Several NASA/JPL mission designs also include asteroid encounters that will take advantage of passes through the asteroid belt as the spacecraft speed toward their next planetary targets.

The Edwin P. Hubble Space Telescope was launched in April 1990. By placing this telescope in orbit above the distortions of the Earth's atmosphere, we will be able to detect objects 100 times fainter than those visible from ground-based telescopes. The Hubble telescope is a complex project that has been coordinated among three NASA centers, private contractors, and several educational institutions. JPL built the telescope's Wide-Field/Planetary Camera, one of its chief instruments.

Among the roster of solar-system targets we shouldn't neglect is the Earth itself. Advanced satellites from the United States and other countries will be launched in the early 1990s to give us a much more comprehensive and detailed view of our planet's climate systems. JPL is preparing instruments such as the NASA Scatterometer, a device for studying ocean winds, due to be launched on a Japanese rocket.

Other JPL projects include TOPEX/POSEIDON, a satellite that will map circulation of the world's oceans, and instruments for the Earth Observing System, a major NASA Earth-observation program.

Apart from such unmanned space projects, JPL also staffs an office near Washington, D.C., that supports the development of NASA's Space Station Freedom. This is a manned laboratory, the components of which will begin to be put in orbit as early as the mid-1990s.

As you follow launches in the years ahead, you will notice changes in the launch vehicles used. Like Magellan and Galileo, Ulysses will be carried into Earth orbit by the space shuttle. After each spacecraft is

released by the shuttle, an upper-stage motor attached to the probe fires and sends the craft off to its destination. Several missions, notably that of Galileo to Jupiter, have undergone many launch scenarios and upper-stage configuration changes before and after the Challenger accident in 1986. Galileo in particular must now take a circuitous path to Jupiter, swinging by the Earth twice and Venus once to pick up gravity-assist energy to compensate for the use of an upper-stage motor that is less powerful than originally planned.

After these missions on the shuttle, we will return to expendable rockets for planetary spacecraft launches. Most of the JPL missions will use Titan IV rockets, more powerful versions of the vehicles that launched the Voyagers. The joint U.S.–French TOPEX/POSEIDON satellite will be launched by the European-built Ariane rocket.

The following pages summarize JPL space projects being developed or under study. At the end is a descriptive summary of mission concepts that are probably farther in the future—and that would take us literally out to the threshold of the stars.

Voyager Interstellar Mission

Twin Voyager spacecraft were launched in 1977 to explore the outer solar system. The Voyagers explored the four giant planets Jupiter, Saturn, Uranus, and Neptune, 48 of their moons, and the planets' unique systems of rings and magnetic fields.

After visiting Jupiter (1979) and Saturn (1980), Voyager 1 is now leaving the solar system, rising above the ecliptic plane at an angle of about 35 degrees, at a rate of about 520 million kilometers (323 million miles) a year. Voyager 2 visited Jupiter (1979), Saturn (1981), Uranus (1986), and Neptune (1989) and is also headed out of the solar system, diving below the ecliptic plane at an angle of about 48 degrees, at about 470 million kilometers (292 million miles) a year.

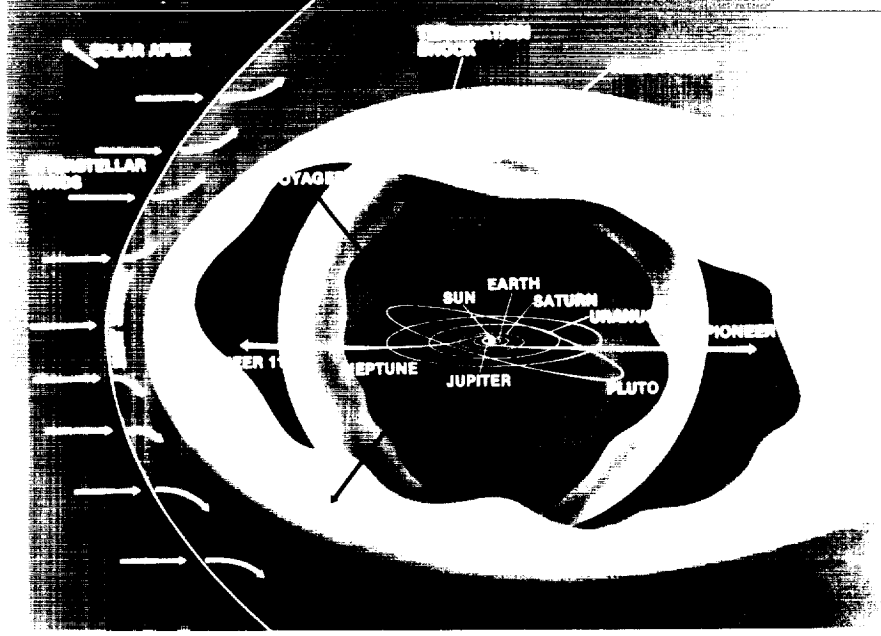
Both spacecraft will continue to study ultraviolet sources among the stars and to search for the boundary between the Sun's influence and interstellar space. If all goes well, we will be able to communicate with them for another 25 to 30 years, until their nuclear power sources can no longer supply enough electrical energy to power critical subsystems.

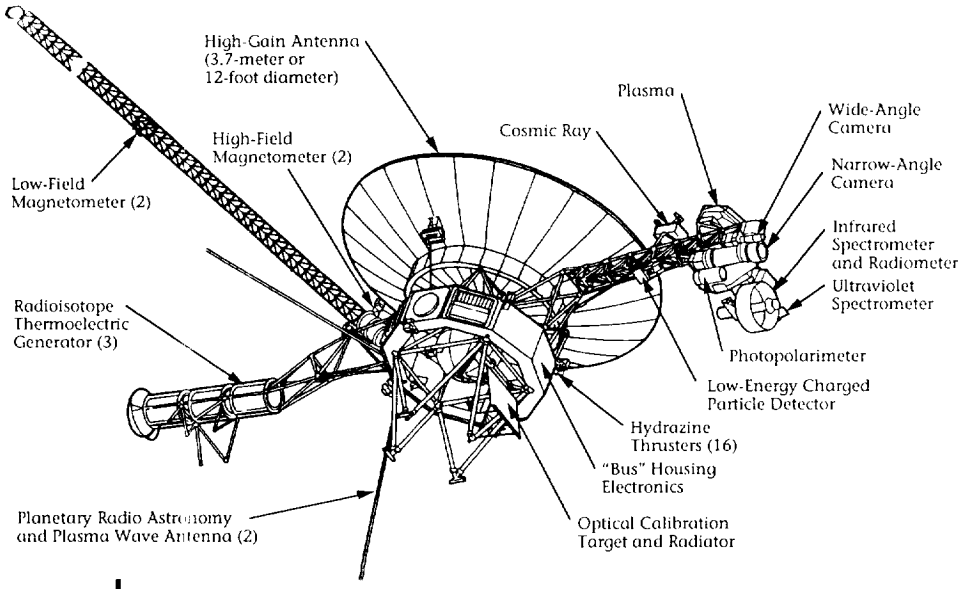
Objectives

- Characterize the boundary between the Sun's magnetic influence and interstellar space
- Study fields and particles in distant interplanetary and interstellar space
- Observe radio emissions from the Sun, the solar wind, and the interstellar medium
- Observe ultraviolet emissions from stellar and extragalactic sources, quasars, the interstellar medium, and the sky background

Active Instruments

- Ultraviolet spectrometer
- Magnetometers
- Plasma detector
- Low-energy charged particles detector
- Cosmic-ray detector
- Planetary radio-astronomy sensor
- Plasma-wave detector





Voyager 1 Jupiter Encounter 3/5/79

Voyager 2 Jupiter Encounter 7/9/79

Voyager 1 Saturn Encounter 11/12/80

Voyager 2 Saturn Encounter 8/25/81

Voyager 2 Uranus Encounter 1/24/86

Voyager 2 Neptune Encounter 8/25/89

Project Start: October 1972
Launch: Voyager 2 — 8/20/77
Voyager 1 — 9/5/77

Voyagers 1 and 2 Interstellar Missions

1978 1980 1982 1984 1986 1988 1990 1992 1994 2015

Galileo

The environment is so complex at Jupiter, the largest planet of our solar system, that the giant and its satellites are like a miniature solar system of their own. We will be able to add significantly to what was learned from the Pioneers and Voyagers when Galileo arrives in 1995 for direct measurements of the Jovian atmosphere and a two-year, close-up tour of the four Galilean moons.

Galileo is the most complex planetary spacecraft ever built. The Galileo orbiter has two sections, one that slowly spins and another that does not. In this way, it combines the best aspects of previous spacecraft: experiments that measure fields and particles are on the spinning segment to cancel out interference from the spacecraft's electronics, while cameras and other instruments that need stability are on the "despun" segment. Five months before reaching Jupiter, the orbiter will release an instrumented probe that will make a parachuted descent into the planet's highly active atmosphere.

On its circuitous route to Jupiter, Galileo will gain energy from a gravity assist at Venus and two from Earth, performing science observations during those encounters, including some unique observations of Earth's Moon. Along the way, Galileo will also encounter two asteroids, Gaspra and Ida, as it traverses the asteroid belt between Mars and Jupiter.

Objectives

- Directly sample Jupiter's atmosphere
- Conduct long-term studies of atmosphere
- Conduct close-up studies of Jovian satellites
- Map structure and dynamics of magnetosphere
- Map thermal properties of planet

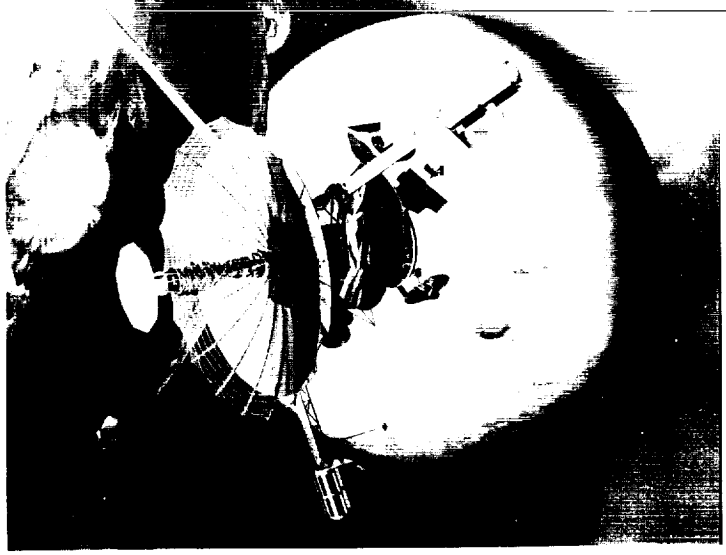
Instruments

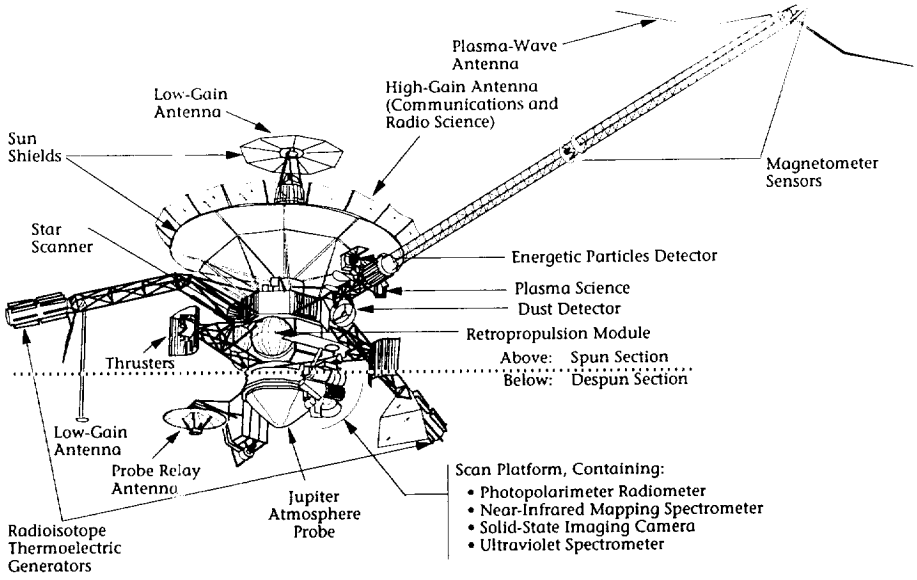
Orbiter

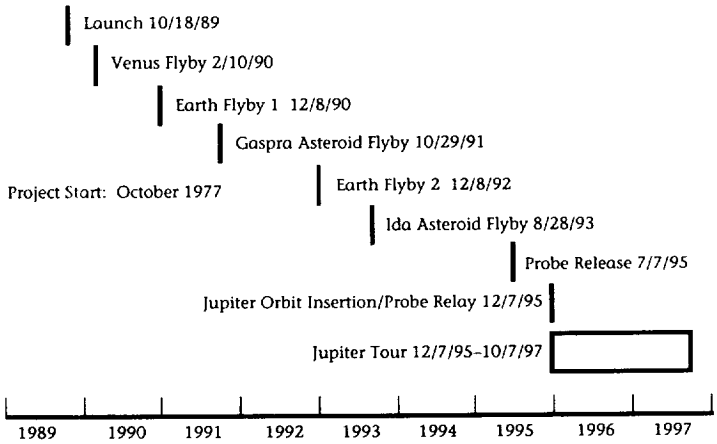
- Four optical sensors
- Four fields-and-particles detectors
- Dust detector
- Radio science (two experiments)

Probe

- Three chemical-analysis instruments
- Cloud detector
- Radiometer
- Lightning and energetic-particle detector




Plasma-Wave Antenna
Low-Gain Antenna
High-Gain Antenna (Communications and Radio Science)
Sun Shields
Magnetometer Sensors
Star Scanner
Energetic Particles Detector
Plasma Science
Dust Detector
Retropropulsion Module
Thrusters
Above: Spun Section
Below: Despun Section
Low-Gain Antenna
Probe Relay Antenna
Jupiter Atmosphere Probe
Scan Platform, Containing:
• Photopolarimeter Radiometer
• Near-Infrared Mapping Spectrometer
• Solid-State Imaging Camera
• Ultraviolet Spectrometer
Radioisotope Thermoelectric Generators


Launch 10/18/89
Venus Flyby 2/10/90
Earth Flyby 1 12/8/90
Gaspra Asteroid Flyby 10/29/91
Project Start: October 1977
Earth Flyby 2 12/8/92
Ida Asteroid Flyby 8/28/93
Probe Release 7/7/95
Jupiter Orbit Insertion/Probe Relay 12/7/95
Jupiter Tour 12/7/95–10/7/97
1989
1990
1991
1992
1993
1994
1995
1996
1997

Wide-Field/Planetary Camera—Hubble Space Telescope

The difference between NASA's Hubble Space Telescope and current ground-based optical telescopes can be compared to the difference between Galileo Galilei's first telescope and its predecessor, the human eye.

This orbiting observatory will detect objects 100 times fainter than those visible from Earth-based telescopes, with about 10 times greater spatial resolution. Our reach into the cosmos will be extended from a present limit of about 2 billion light-years to roughly 15 billion light-years, allowing us to look back in time nearly to the beginning of the universe.

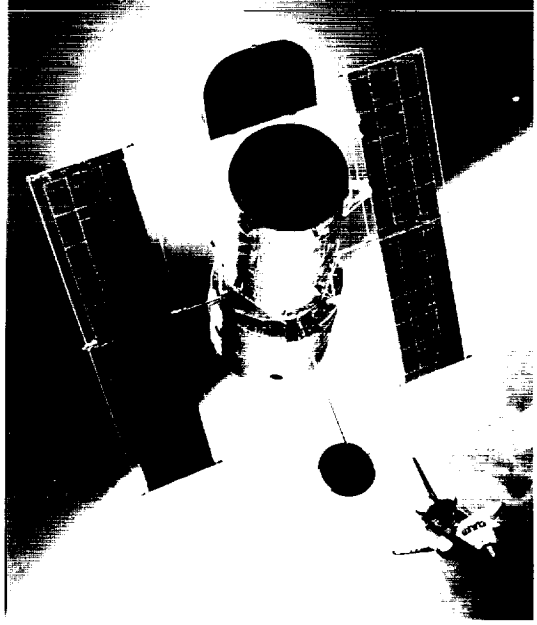
JPL's contribution to this project is the Wide-Field/Planetary Camera, one of the telescope's main science instruments. This camera operates in two modes: the "wide-field" mode views large areas of sky, allowing scientists to plot the spatial relationships of distant objects such as galaxies and quasars; the "planetary" mode views a narrower field and is designed for the study of objects within the solar system.

Objectives

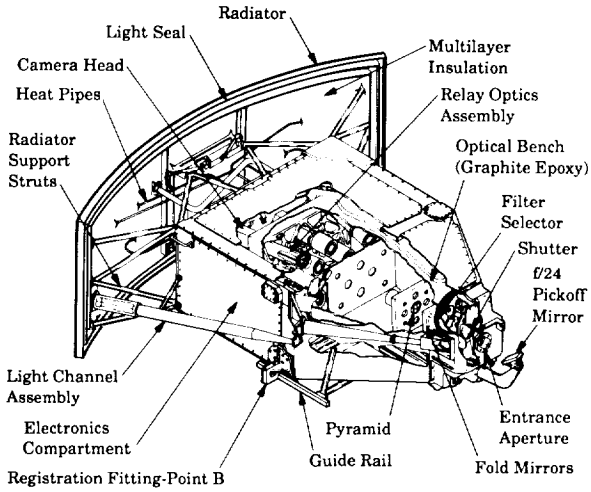
- Study cosmic evolution and distances
- Image stars and galaxies
- Conduct star- and galaxy-motion studies
- Map interstellar energy distribution
- Search for planets around Sun and other stars
- Image planetary atmospheres and surfaces, satellites, asteroids, and comets

Hubble Space Telescope Instruments

- Wide-Field/Planetary Camera
- Faint-object spectrograph
- High-resolution spectrograph
- High-speed photometer
- Faint-object camera
- Fine-guidance sensors



Hubble Space Telescope



Wide-Field/ Planetary Camera

Launch April 1990

Orbital Verification (2 months)

Science Verification (6 months)

Science Operations

Science Observations

End of Mission 2005+

Project Start: October 1977

1989 1990 1991 1992 1993 1994 1995 1996 1997

Ulysses

Astronomers have learned that the Sun, a seemingly homogeneous ball of light and heat, is in fact a complex realm of diverse structural, thermodynamic, and nuclear phenomena. Until now, we have been able to study only the plasmas and particles streaming from the Sun from a perspective within the ecliptic—the two-dimensional plane in which the Earth and most of the planets orbit the Sun.

Ulysses, a joint mission between the European Space Agency (ESA) and NASA, will add a third dimension to this view by studying the Sun, solar wind, and interstellar space at almost all solar latitudes. After launch from the space shuttle, the ESA-developed Ulysses spacecraft will travel first to Jupiter, where the gravity of the giant planet will deflect the spacecraft's path out of the ecliptic. Ulysses will then travel over the poles of the Sun to study the solar environment for several years with its ESA- and NASA-supplied instruments.

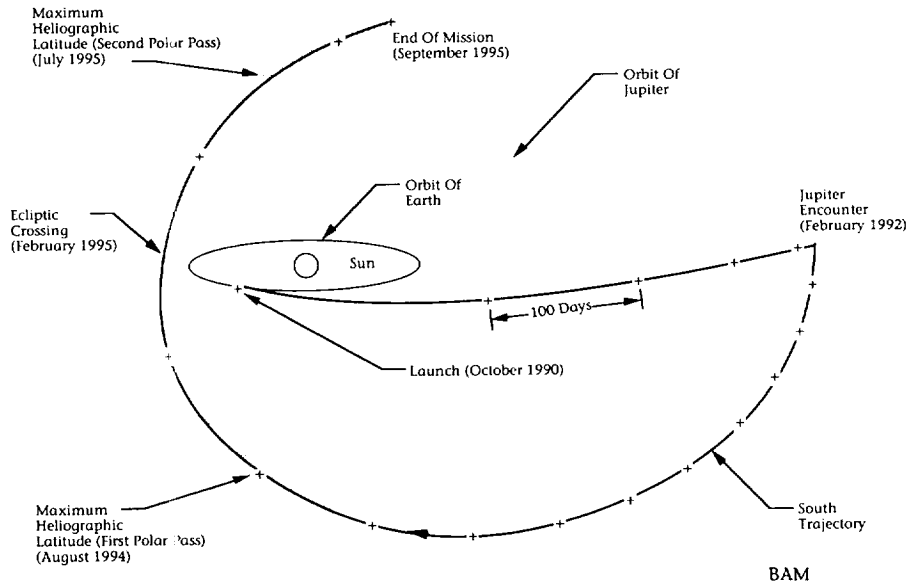
Objectives

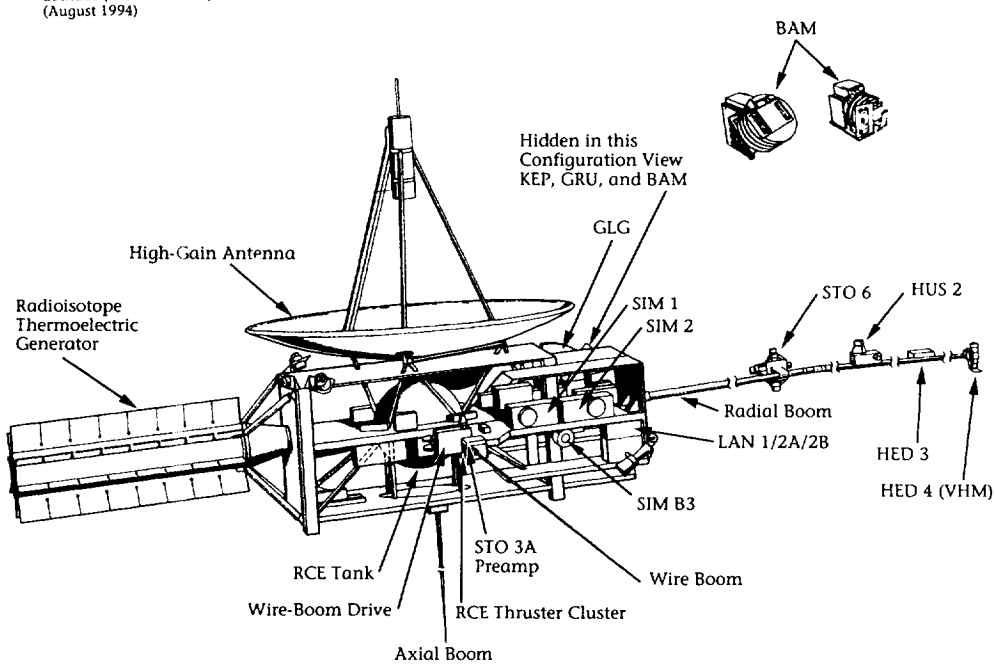
- Conduct fields-and-particles exploration of Sun's polar regions and regions far from ecliptic plane
- Characterize inner heliosphere at all solar latitudes

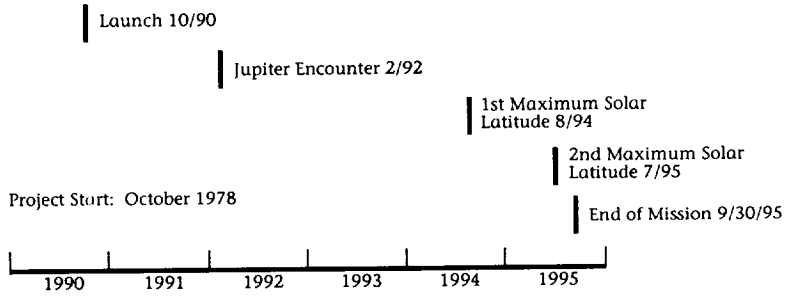
Instruments

- Magnetometers (HED)
- Seven particle/wave/plasma detectors
  - Solar-wind plasma (BAM)
  - Solar-wind ions (GLG)
  - Low-energy ions and electrons (LAN)
  - Energetic particles and interstellar gas (KEP)
  - Cosmic ray/solar particles (SIM)
  - Unified radio and plasma waves (STO)
  - Solar X-rays/cosmic gamma-ray bursts (HUS)
- Dust detector (GRU)
- Radio science
  - Coronal sounding
  - Gravitational wave

Note: The letter symbols are keyed to the diagram of the spacecraft on the next page.


Maximum Heliographic Latitude (Second Polar Pass) (July 1995)
End Of Mission (September 1995)
Orbit Of Jupiter
Orbit Of Earth
Ecliptic Crossing (February 1995)
Jupiter Encounter (February 1992)
Sun
100 Days
Launch (October 1990)
Maximum Heliographic Latitude (First Polar Pass) (August 1994)
South Trajectory


BAM
Hidden in this Configuration View KEP, GRU, and BAM
GLG
High-Gain Antenna
Radioisotope Thermoelectric Generator
SIM 1
SIM 2
STO 6
HUS 2
Radial Boom
LAN 1/2A/2B
HED 3
HED 4 (VHM)
SIM B3
STO 3A Preamp
RCE Tank
Wire Boom
Wire-Boom Drive
RCE Thruster Cluster
Axial Boom


Launch 10/90
Jupiter Encounter 2/92
1st Maximum Solar Latitude 8/94
2nd Maximum Solar Latitude 7/95
Project Start: October 1978
End of Mission 9/30/95
1990
1991
1992
1993
1994
1995

TOPEX/POSEIDON

What causes the devastation of a climate phenomenon like the El Niño currents in the Pacific? Why do continents experience droughts one year and flooding another? To help answer these questions, scientists are collaborating on an array of international experiments and studies in the 1990s to better understand interactions between the world's oceans and long-term weather trends.

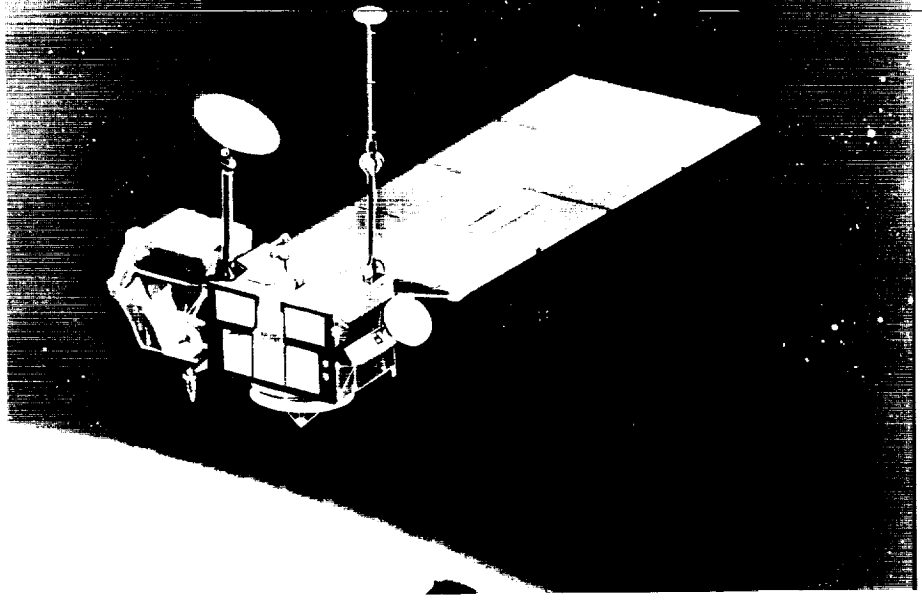
NASA's Ocean Topography Experiment, or TOPEX, and France's POSEIDON mission have been combined to make highly detailed and accurate maps of sea level around the world. Sea level is related to ocean currents and eddies and, by taking gravity into account, researchers will also be able to identify major features of the ocean floors. The U.S.-built spacecraft will be launched by a French Ariane rocket and carry instruments contributed by both countries. Its primary mission will span three years.

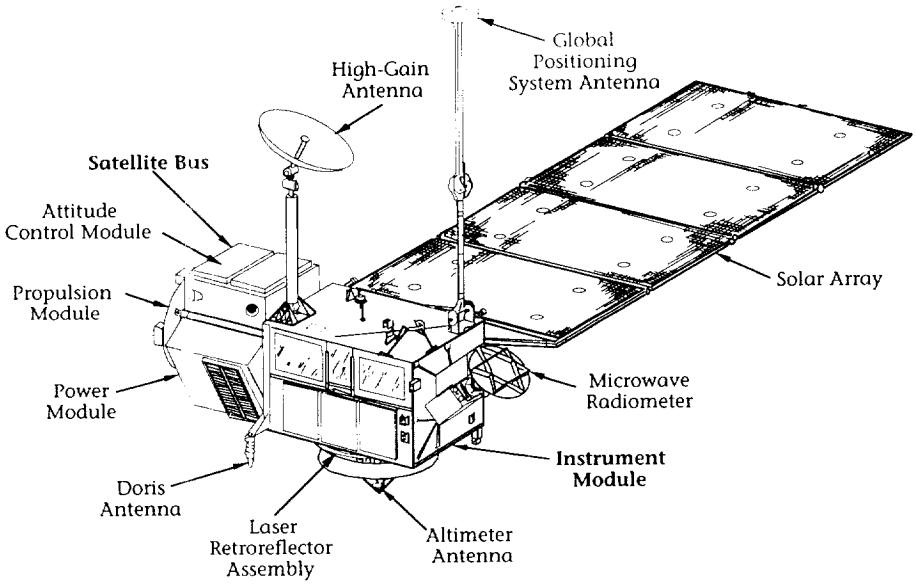
Objectives

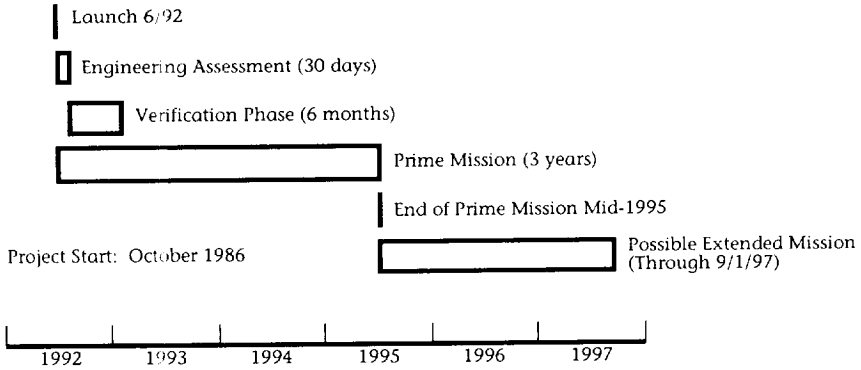
- Observe ocean topography for several years, supporting global studies of
  - Ocean circulation and variability
  - Ocean dynamics and role in climate
  - Circulation/wind interactions
  - Current/wave interactions
  - Heat, mass, nutrient, and salt transport
  - Tides

Instruments

- Two altimeters
- Microwave radiometer
- Laser retroreflector
- Two satellite-positioning systems




Global Positioning System Antenna
High-Gain Antenna
Satellite Bus
Attitude Control Module
Propulsion Module
Power Module
Solar Array
Microwave Radiometer
Instrument Module
Doris Antenna
Laser Retroreflector Assembly
Altimeter Antenna


Launch 6/92
Engineering Assessment (30 days)
Verification Phase (6 months)
Prime Mission (3 years)
End of Prime Mission Mid-1995
Project Start: October 1986
Possible Extended Mission (Through 9/1/97)
1992
1993
1994
1995
1996
1997

Mars Observer

Much as Magellan at Venus will improve on the missions before it, Mars Observer will provide views of the red planet beyond those possible from the Viking Orbiters launched in 1975. The spacecraft is the first in a series called Planetary Observer, which adapts the bus of a satellite typically used only for Earth-orbiting missions for use as a general inner-solar-system explorer. Mars Observer is scheduled for launch in 1992 with a Titan III rocket and Transfer Orbit Stage, a new upper-stage concept.

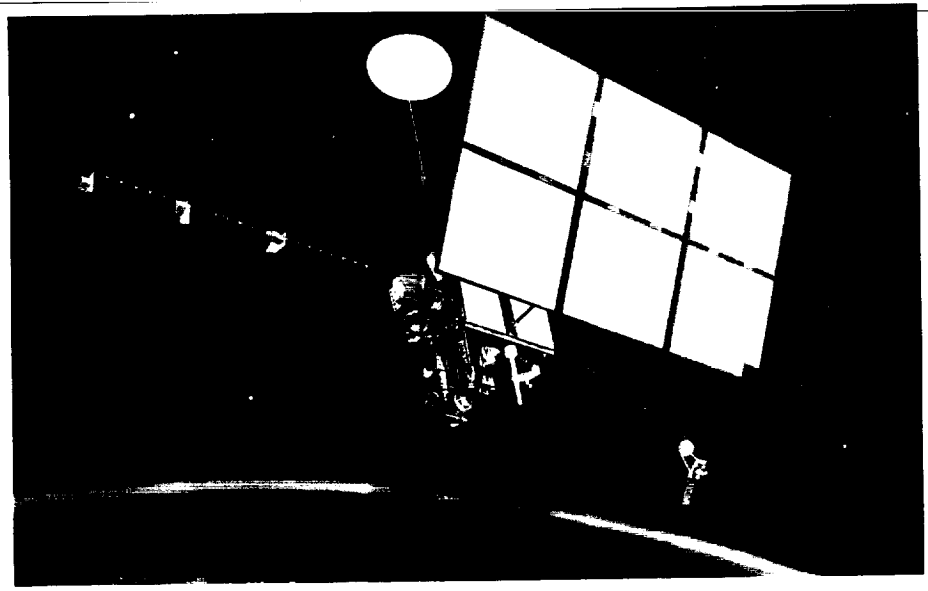
The mission's chief purpose is to study the surface, atmosphere, and climate of Mars throughout a full Martian year of 687 Earth days. Imaging from an orbit lower than that of the Viking Orbiters, the Mars Observer camera will produce panoramic, high-resolution surface maps useful for planning future lander missions. The spacecraft will also contain French-built equipment to relay data from surface-exploration balloons released by the Soviet Union's Mars '94 mission. Ten Soviet scientists are directly participating in Mars Observer studies.

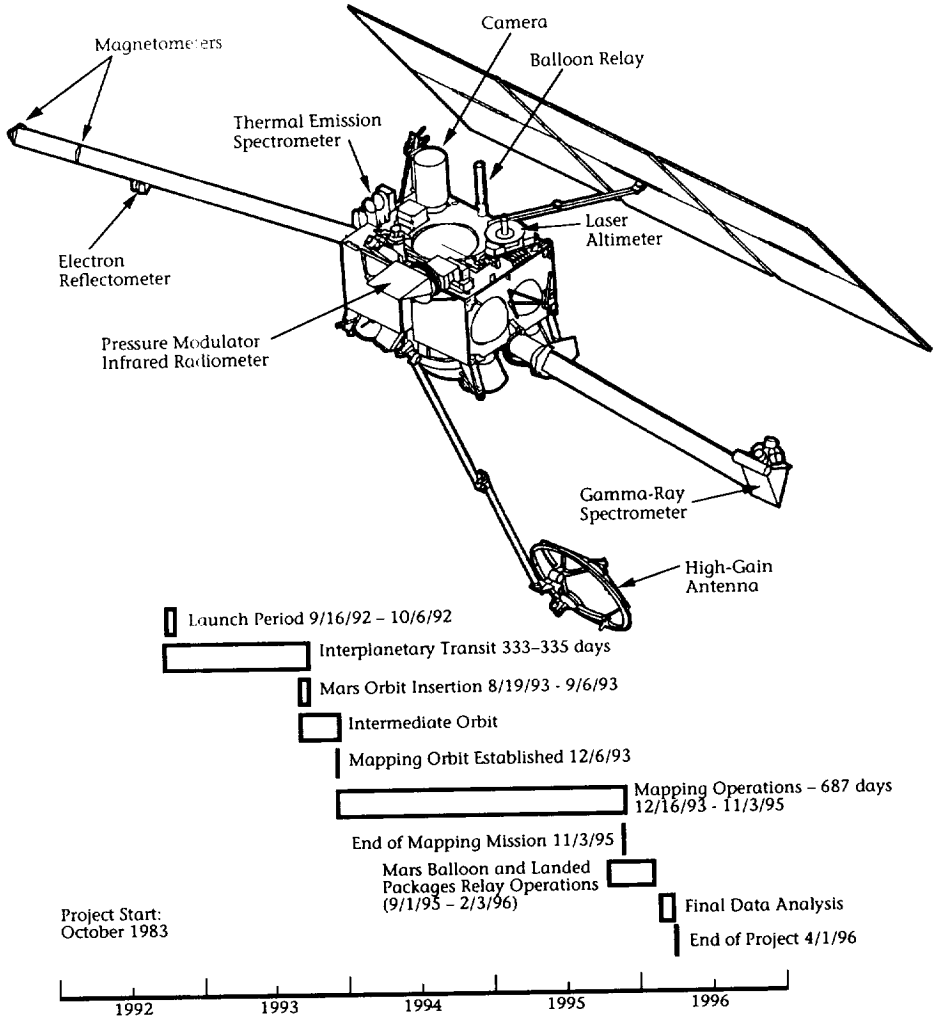
Objectives

- Conduct global studies of
  - Mineralogical and elemental composition of surface
  - Distribution of surface minerals
  - Topography and magnetic field
  - Gravitational field
  - Seasonal movement of water and dust
  - Atmospheric circulation

Instruments

- Gamma-ray spectrometer
- Laser altimeter
- Wide-angle, high-resolution camera
- Two thermal-emission detectors
- Magnetometer
- Pressure and infrared detectors
- Mars '94 balloon data relay
- Radio science




Magnetometers
Camera
Balloon Relay
Thermal Emission Spectrometer
Laser Altimeter
Electron Reflectometer
Pressure Modulator Infrared Radiometer
Gamma-Ray Spectrometer
High-Gain Antenna
Launch Period 9/16/92 – 10/6/92
Interplanetary Transit 333–335 days
Mars Orbit Insertion 8/19/93 - 9/6/93
Intermediate Orbit
Mapping Orbit Established 12/6/93
Mapping Operations – 687 days
12/16/93 - 11/3/95
End of Mapping Mission 11/3/95
Mars Balloon and Landed Packages Relay Operations (9/1/95 – 2/3/96)
Final Data Analysis
End of Project 4/1/96
Project Start: October 1983
1992
1993
1994
1995
1996

Comet Rendezvous Asteroid Flyby

The more scientists learn about comets, the more they are intrigued. For years, it has been suspected that comets were very primitive objects from the outer solar system, essentially unchanged from the era in which the solar system formed, and that they may have originally brought water to the inner planets. Data retrieved from the international missions to Comet Halley in 1986 suggested that comet nuclei contain organic compounds, which raises questions about their role in the creation of life on Earth.

Comet Rendezvous Asteroid Flyby, or CRAF, will extend the Halley experience by meeting Comet Kopff near the orbit of Jupiter and traveling along with it for at least three years as the comet loops around the Sun. It will also launch a penetrator–lander that will directly sample the comet's nucleus. On the way to Kopff, CRAF will encounter the asteroid Hamburga. CRAF will be the first in a new series of outer planet exploration missions using the JPL-designed Mariner Mark II spacecraft bus.

Objectives

Comet Rendezvous

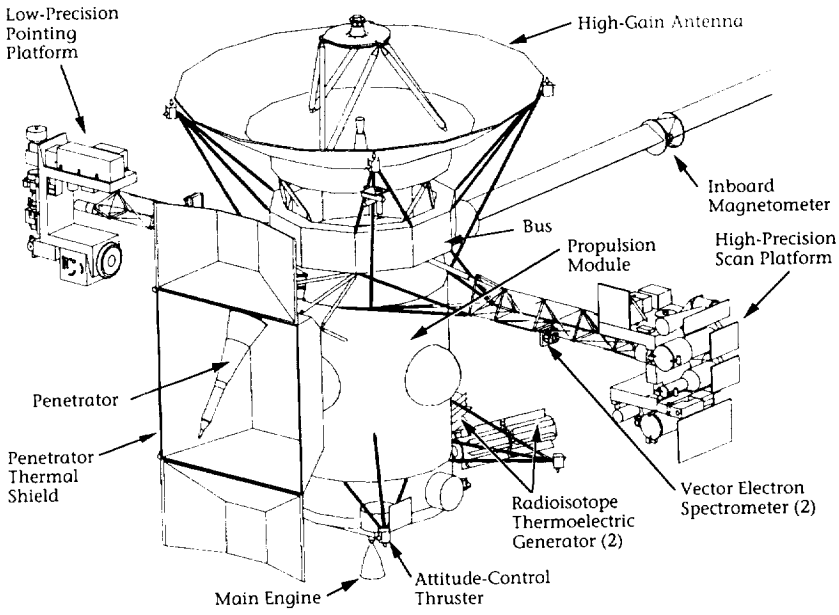
- Characterize comet nucleus and coma
- Study process of comet tail formation
- Study tail dynamics and interactions with radiation and solar wind

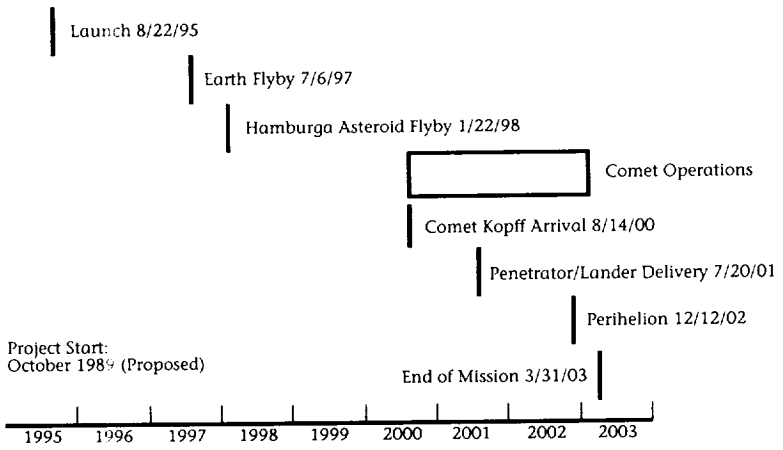
Asteroid Flyby

- Characterize structure and geology
- Determine distribution of minerals, metals, and ices
- Measure mass, density, and nearby environment

Instruments

- Comet penetrator–lander (includes temperature probes and surface strength and composition sensors)
- Charge-coupled device narrow- and wide-angle cameras
- Near- and far-infrared spectrometers
- Seven particle/dust/ice/gas/plasma analyzers
- Magnetometer
- Radio science


Low-Precision Pointing Platform
High-Gain Antenna
Inboard Magnetometer
Bus
Propulsion Module
High-Precision Scan Platform
Penetrator
Penetrator Thermal Shield
Vector Electron Spectrometer (2)
Radioisotope Thermoelectric Generator (2)
Attitude-Control Thruster
Main Engine


Launch 8/22/95
Earth Flyby 7/6/97
Hamburga Asteroid Flyby 1/22/98
Comet Operations
Comet Kopff Arrival 8/14/00
Penetrator/Lander Delivery 7/20/01
Perihelion 12/12/02
Project Start:
October 1989 (Proposed)
End of Mission 3/31/03
1995
1996
1997
1998
1999
2000
2001
2002
2003

Cassini

Cassini will follow CRAF as the second mission in the new Mariner Mark II series of spacecraft to the outer solar system. Named for the Franco-Italian astronomer who discovered the gap in Saturn's rings (as well as several Saturnian moons), Cassini will journey to the ringed planet for four years of orbital studies.

A probe provided by the European Space Agency and carried to Saturn by the orbiter will descend to the surface of Titan, Saturn's largest moon. Named Huygens for the Dutch scientist who discovered Titan, the probe will study the atmosphere of the moon, which the Voyagers showed to have organic chemistry similar to that of simple precursors to life. If it survives the descent, the probe will continue to relay (for several minutes only) data from Titan's surface, which may be covered with puddles or even oceans of liquid ethane.

Objectives

- Conduct detailed studies of Saturn's atmosphere, rings, and magnetosphere
- Conduct close-up studies of Saturnian satellites
- Characterize Titan's atmosphere and surface

Instruments

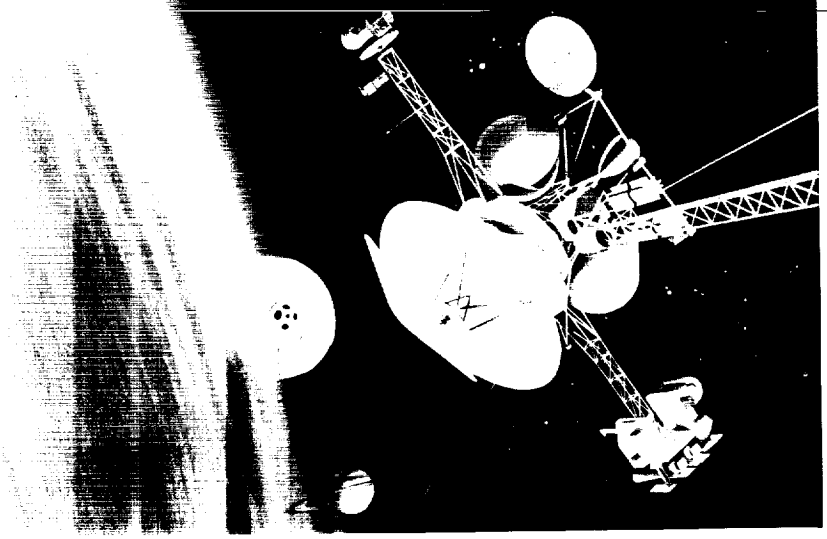
Orbiter

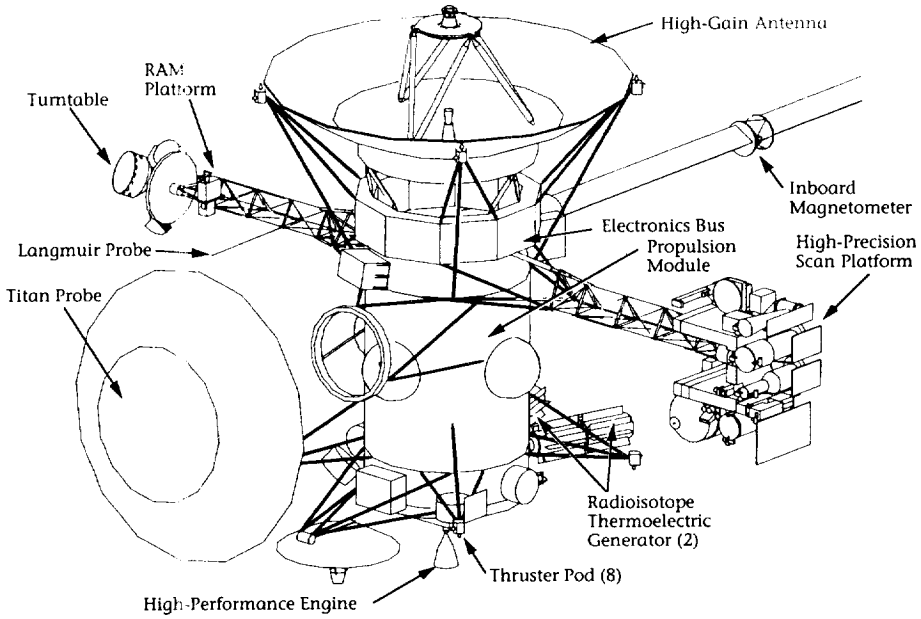
- Six optical sensors
- Nine fields-and-particles detectors
- Titan radar mapper
- Radio science

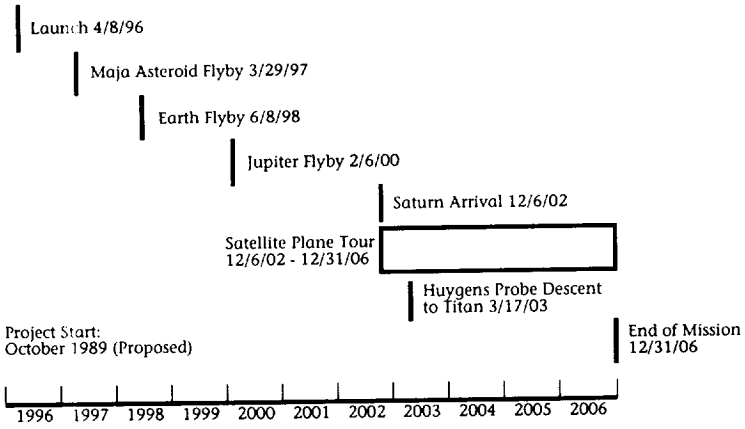
Probe

- Five atmospheric-characterization instruments
- Descent imager and radiometer
- Radar altimeter
- Lightning and radio-emission detector
- Surface science package

Note: Above instruments from model (not approved) payload.




High-Gain Antenna
RAM Platform
Turntable
Inboard Magnetometer
Electronics Bus
Propulsion Module
High-Precision Scan Platform
Langmuir Probe
Titan Probe
Radioisotope Thermoelectric Generator (2)
Thruster Pod (8)
High-Performance Engine


Launch 4/8/96
Maja Asteroid Flyby 3/29/97
Earth Flyby 6/8/98
Jupiter Flyby 2/6/00
Saturn Arrival 12/6/02
Satellite Plane Tour 12/6/02 - 12/31/06
Huygens Probe Descent to Titan 3/17/03
Project Start: October 1989 (Proposed)
End of Mission 12/31/06
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006

Lunar Observer

The Lunar Observer (LO) spacecraft will map the Moon from polar orbit for at least two years, gathering global information about the Moon's surface, subsurface, atmosphere, magnetic and gravitational fields, and radio-frequency environment. Such data will contribute to a future human outpost and other facilities. The mission will search for frozen water at the lunar poles and map concentrations of metals, oxides, and other potentially useful resources. In addition, LO will address important scientific questions relating to the origin and evolution of the Moon and its importance to similar questions about the Earth.

Lunar Observer is currently envisaged as a two-spacecraft mission. Each will release a tiny lunar satellite that will enable measurement of the Moon's gravity field.

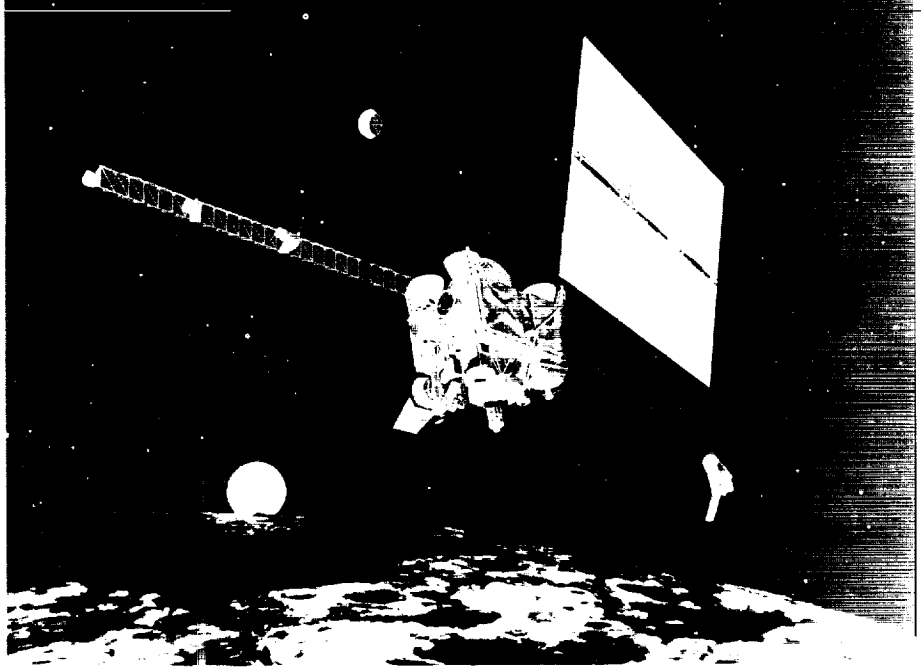
Objectives

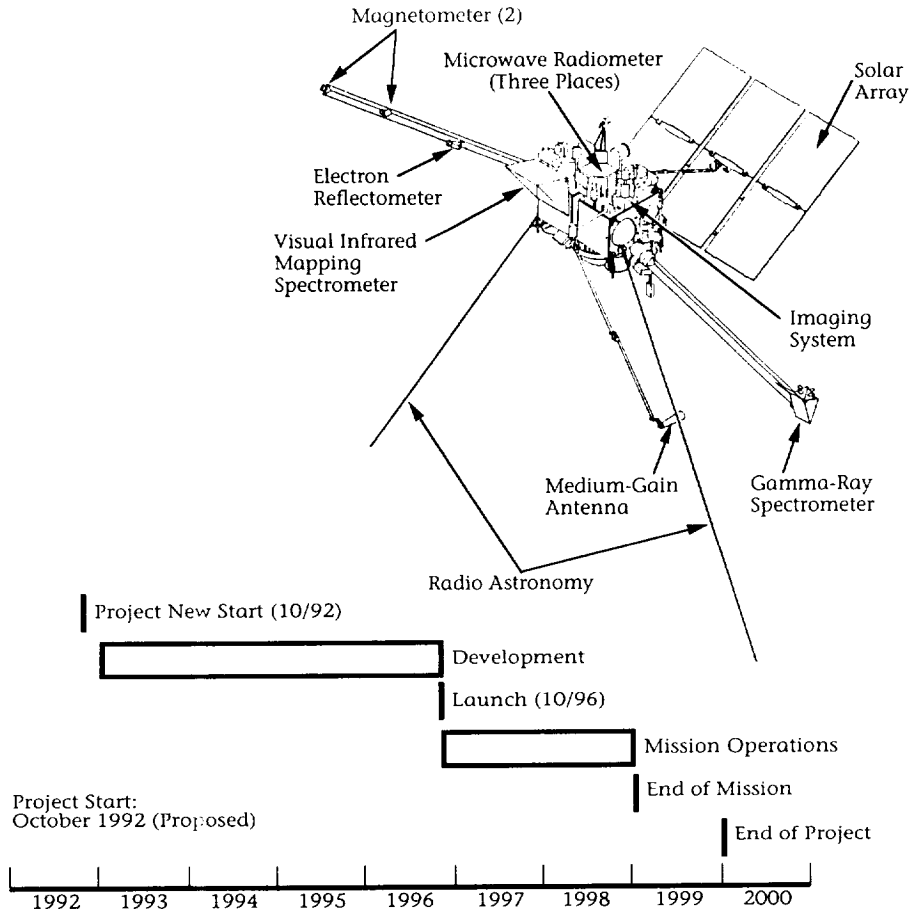
- Measure global elemental and mineralogical surface composition
- Assess global resources, including possible frozen volatiles at the poles
- Measure lunar gravity and magnetic fields
- Measure global figure and surface topography
- Measure global atmosphere and plasma density/composition and dust distributions
- Estimate characteristics of the deep lunar mantle and core
- Perform global, regional, and local mapping and analysis in support of NASA's Space Exploration Initiative experiment

Instruments

- Thermal emission spectrometer
- Gamma-ray/X-ray spectrometers
- Laser altimeter
- Magnetometer/electron reflectometer
- Visual infrared mapping spectrometer
- Imaging subsystem
- Microwave radiometer
- Gravity measurement system
- Ultraviolet spectrometer
- Ion mass spectrometer
- Neutral mass spectrometer
- Radio astronomy

Note: These instruments are from a model payload.




Magnetometer (2)
Microwave Radiometer (Three Places)
Solar Array
Electron Reflectometer
Visual Infrared Mapping Spectrometer
Imaging System
Medium-Gain Antenna
Gamma-Ray Spectrometer
Radio Astronomy

Project New Start (10/92)
Development
Launch (10/96)
Mission Operations
End of Mission
End of Project
Project Start:
October 1992 (Proposed)
1992
1993
1994
1995
1996
1997
1998
1999
2000

Earth Observing System Synthetic Aperture Radar (EOS SAR)

The EOS SAR mission is the product of a 20-year development program that started with NASA's Seasat mission in 1978 and includes the Shuttle Imaging Radar A, B, and C missions (1982, 1984, and 1993, respectively).

In 1999, a medium launch vehicle will carry the EOS SAR on a dedicated spacecraft to a polar orbit 620 kilometers (385 miles) above Earth.

From the polar orbit, the radar will produce data that will be highly synergistic to data from the EOS A and B platforms, which will be developed and launched by NASA's Goddard Space Flight Center. These data will be vital to the interdisciplinary modeling studies that are the heart of the EOS program.

The radar is a multipolarized, multifrequency instrument operating in the X-, C-, and L-bands.

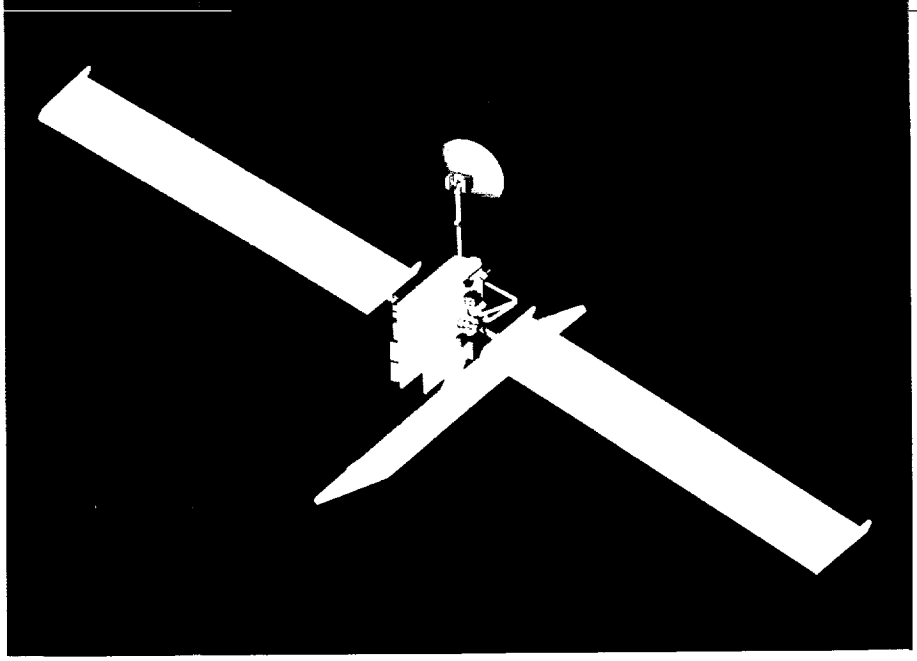
The mission will last 15 years, during which time the SAR may have to be replaced. The current mission concept includes three launches (one initial SAR instrument and two replacements); however, the possibility of fewer launches is under study.

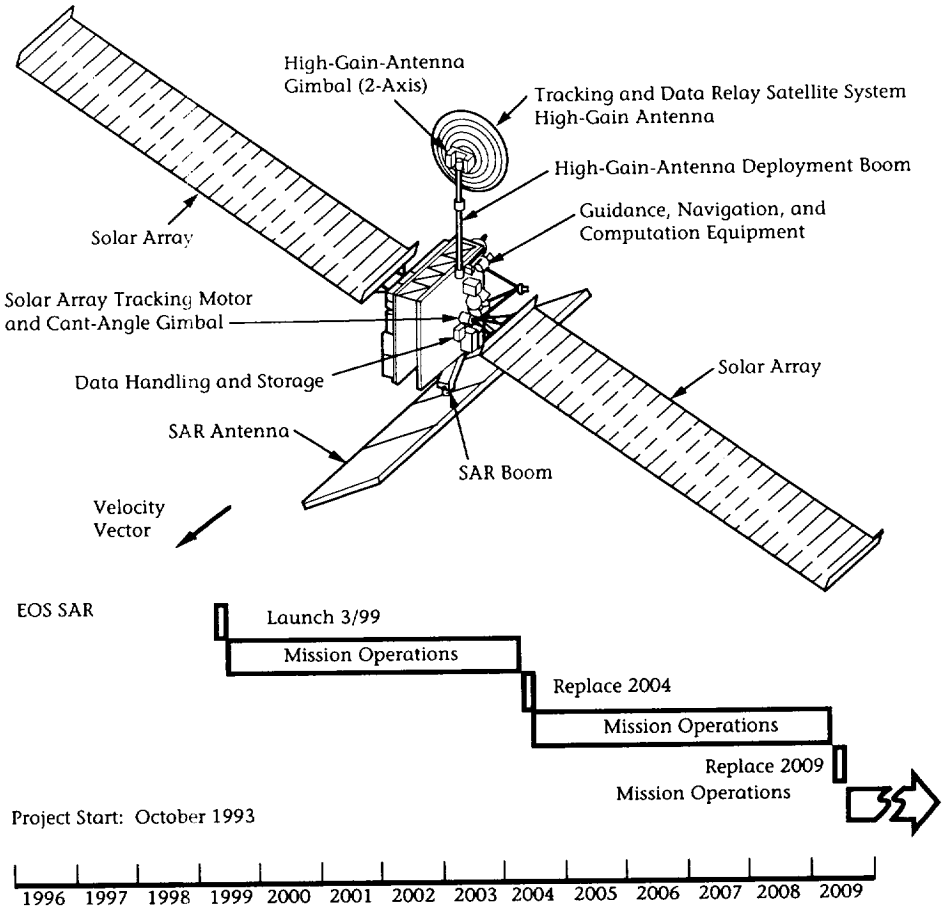
Objectives

- Estimate polar heat flux
- Measure extent and variation of polar ice
- Measure water storage in
  - soil
  - vegetation
  - snow and ice
- Measure carbon storage and flux in global biomass
- Conduct global high-resolution mapping

Instruments (JPL provided)

- Multipolarization, multifrequency synthetic-aperture radar




High-Gain-Antenna
Gimbal (2-Axis)
Tracking and Data Relay Satellite System
High-Gain Antenna
High-Gain-Antenna Deployment Boom
Guidance, Navigation, and
Computation Equipment
Solar Array
Solar Array Tracking Motor
and Cant-Angle Gimbal
Data Handling and Storage
Solar Array
SAR Antenna
SAR Boom
Velocity
Vector

EOS SAR
Launch 3/99
Mission Operations
Replace 2004
Mission Operations
Replace 2009
Mission Operations
Project Start: October 1993
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

Space Infrared Telescope Facility

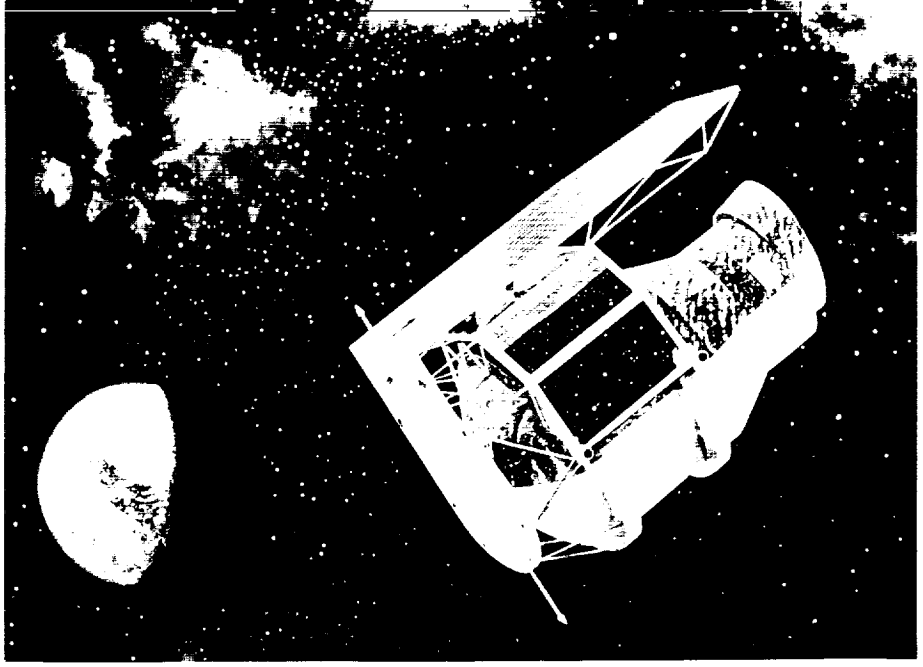
Although not formally approved, the Space Infrared Telescope Facility (SIRTF) is planned as one of the great observatories scheduled to become operational in Earth orbit during the 1990s. Other NASA observatories include the Hubble Space Telescope, the Gamma Ray Observatory, and the Advanced X-Ray Astrophysics Facility. Working together, these astrophysical observatories will cover all of the electromagnetic spectrum from gamma rays through far infrared.

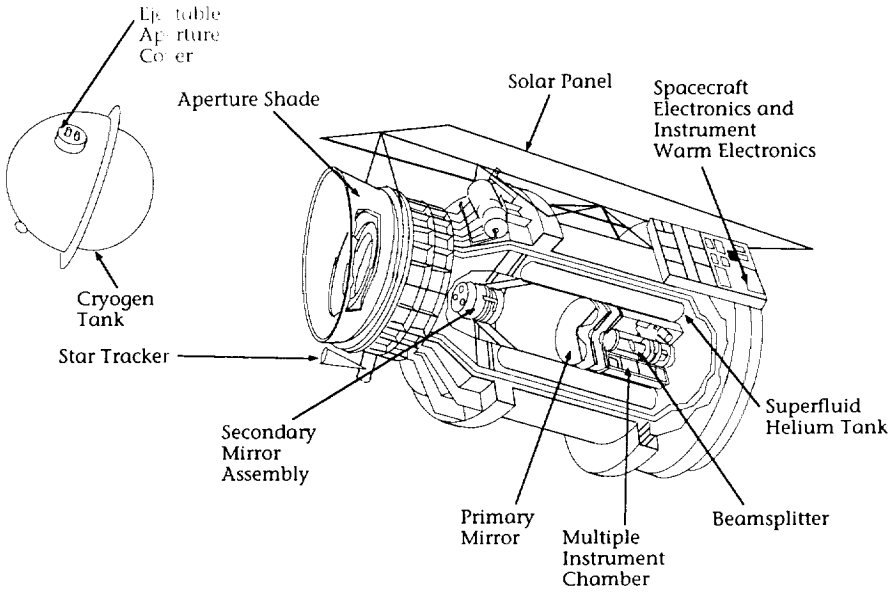
Objectives

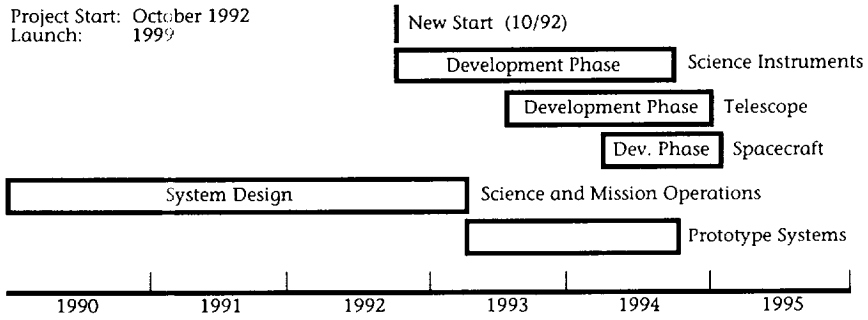
- Characterize conditions in the early solar system
- Extend the search for planets in other solar systems
- Study star formation
- Enhance knowledge of the chemical and physical conditions in space
- Investigate the core of our galaxy
- Provide detailed pictures of infrared galaxies
- Search for and study infrared quasars
- Survey small areas of the sky at high sensitivity
- Search for the galaxy's "missing mass" in brown dwarfs
- Observe primordial galaxies and cosmic evolution

Instruments

- Infrared array camera
- Infrared spectrograph
- Multiband imaging photometer




Ejectable Aperture Cover
Aperture Shade
Solar Panel
Spacecraft Electronics and Instrument Warm Electronics
Cryogen Tank
Star Tracker
Secondary Mirror Assembly
Superfluid Helium Tank
Primary Mirror
Multiple Instrument Chamber
Beamsplitter


Project Start: October 1992
Launch: 1999
New Start (10/92)
Development Phase
Science Instruments
Development Phase
Telescope
Dev. Phase
Spacecraft
System Design
Science and Mission Operations
Prototype Systems
1990
1991
1992
1993
1994
1995

Mars Exploration Initiatives

On the twentieth anniversary of the first landing of men on the Moon, President George Bush called for a return to the Moon, and then a "journey into tomorrow," a mission to Mars.

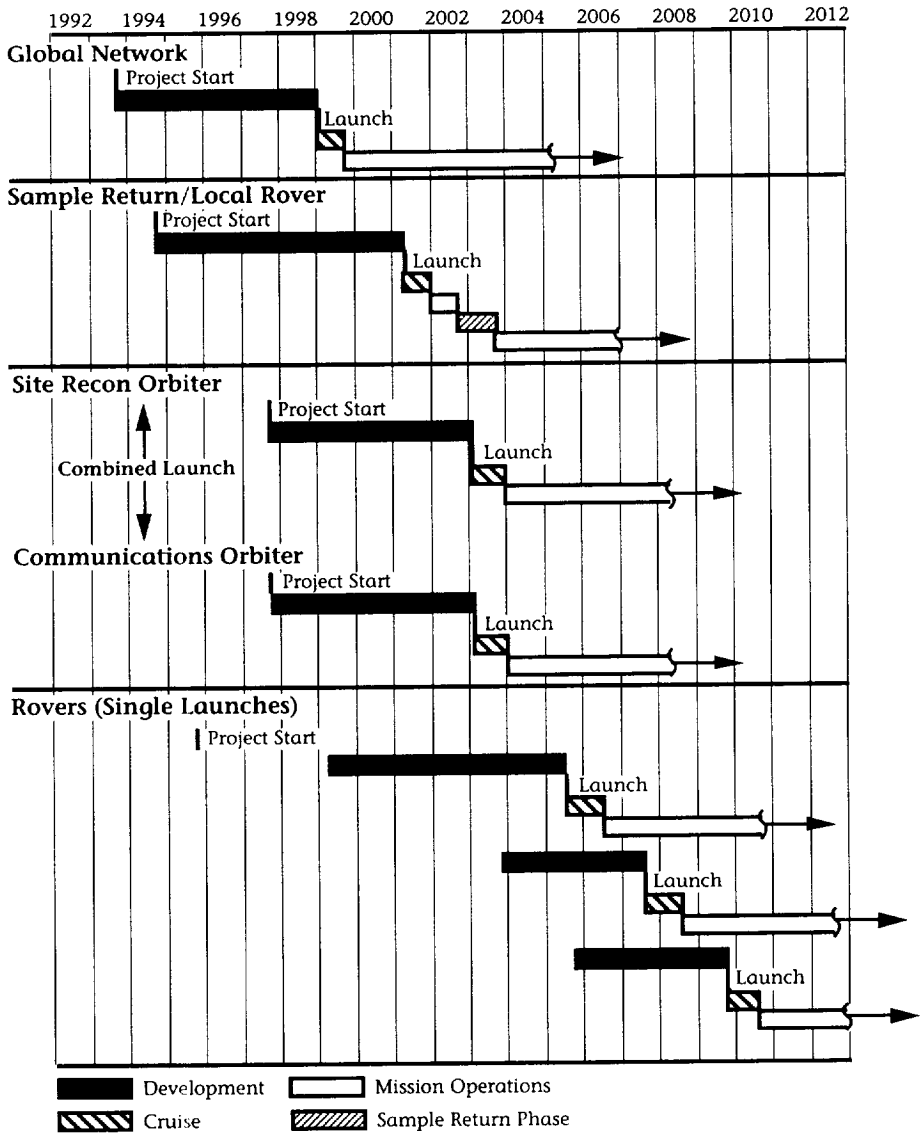
Mars, the red planet, holds a special allure for humankind as a possible second home. Sending the first people to Mars will be a bold and risky undertaking, requiring careful planning, a financial commitment, and as much advance information as possible about the Martian environment to assure a safe and successful venture.

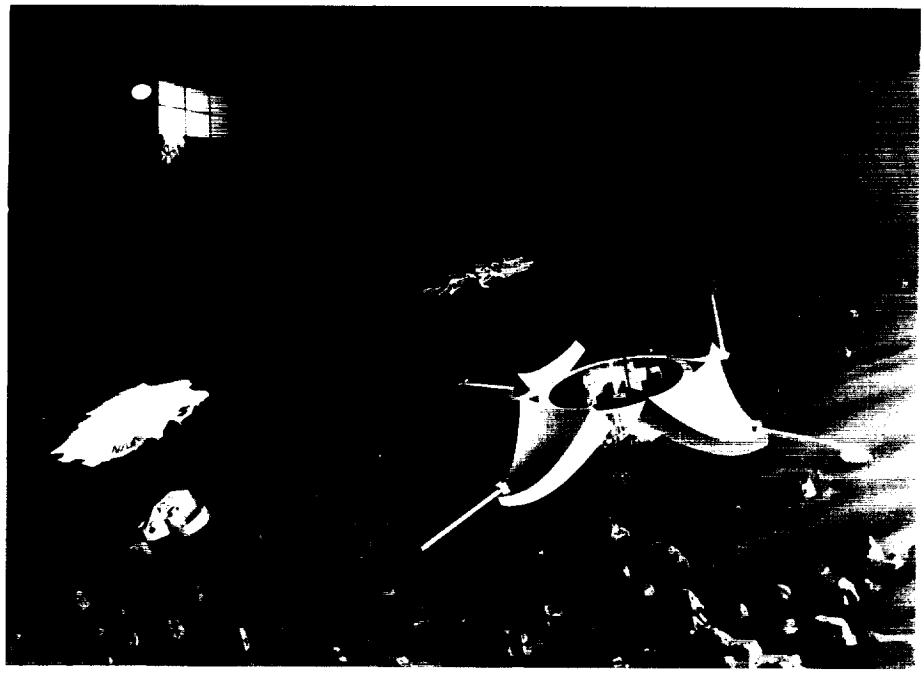
A set of robotic Mars exploration missions is currently being studied. These missions will obtain data required for the design and development of subsequent human exploration missions, demonstrate new technology and new operations concepts, and advance the state of scientific knowledge of Mars.

These missions include the Mars Observer spacecraft, scheduled for launch in 1992; a network of seismological and meteorological stations

An envisioned 2001 Mars mission.

on Mars; a mission to return samples of Martian soil and atmosphere to Earth; an orbiting mission to scout landing sites; an orbiter to act as a relay station between the other orbiters, surface stations, and Earth; and a series of surface rovers to scout specific sites selected from the orbital data.





Lander and Penetrator of the Mars Global Network

1998 Mars Global Network

Seismic and meteorological stations scattered over the Martian surface will provide a unique global network to gather knowledge about local resources, weather, dust storms, soil toxicity, and landing hazards. As early as December 1998, spacecraft carrying surface stations and surface penetrators could be launched to Mars. These landers will be parachuted to the surface from orbit and will collect data as they enter the Martian atmosphere. Some will penetrate the Martian surface, while others will soft-land and collect data for as long as 10 years.

2001 Mars Sample Return With Local Rover

A Mars sample return mission will collect samples of the Martian soil and atmosphere for detailed analysis on Earth, enabling a biological assessment of Mars, tests of surface mobility and Earth-to-Mars communications, and major advances in Mars science. Early sample return missions will include a limited-range rover to collect samples in the vicinity of the landing site.

As the sample return mission is currently envisaged, a biconic aeroshell will carry the surface and return elements to Mars orbit. Next, the landing system, including the Mars ascent vehicle, the local rover and its lander, and a geophysical/meteorological station package, will be landed close to one of the global-network lander sites. Following surface operations of about one year, the collected samples will be launched from Mars to rendezvous with the sample return orbiter in Mars orbit. The samples will be transferred to the Earth-return vehicle for the 7-month trip back to Earth, where the sample return capsule will be plucked from Earth orbit by the shuttle or some other orbital maneuvering vehicle.

2003 Mars Site Reconnaissance and Communications Orbiters

Two Mars orbiting spacecraft will be launched in tandem aboard a single launch vehicle. The Site Reconnaissance Orbiter will map possible landing sites at high resolution, while the Communications Orbiter will serve as a relay station between Mars orbiters, landers, and Earth. The Site Reconnaissance Orbiter will add to the database necessary for detailed planning before astronauts can be sent to Mars.

2005 Mars Rover

Extended rover missions will certify human landing sites, collect and analyze diverse rock samples, and perhaps cache samples for later collection by a sample return mission or by human explorers.

A rover launched in 2005 would arrive in 2006. For the first year, the rover will range over an area of about 100 square kilometers (38.6 square miles) and then will focus on smaller areas for the selection of locations for a power plant, a habitat, and a landing site for human missions. During the second year, the rover will extend its original range to locate useful resources and collect more samples. Its primary mission will last 4 years.

Subsequent rovers could be launched in 2007 and 2009 to explore other Martian regions. All of the rovers will be supported by the Mars Communications Orbiter.

Mission Concepts

In addition to the current space projects with organized teams, many other mission concepts are under study at JPL. Some may be proposed as missions for the 1990s, while others are possible projects for the early 21st century. Examples include

Solar Probe

Heavily shielded to survive the thermal and radiation environment close to the Sun, this spacecraft would venture within four solar radii of the Sun to study the solar corona and other processes near the Sun.

Pluto Flyby

A flight to Pluto, the only planet not yet visited by a spacecraft, would take 14 years, due to Pluto's great distance from Earth. Pluto's moon Charon is about half the size of the planet. Because Charon orbits very close to Pluto, observers using telescopes find it difficult to distinguish between them.

Although apparently one of the rockiest objects in the outer solar system, Pluto has substantial amounts of methane and an atmosphere that forms and decays depending on Pluto's proximity to the Sun.

Rosetta: Comet Nucleus Sample Return

A collaborative effort between JPL and the European Space Agency, Rosetta would acquire and return to Earth samples of a comet nucleus core, a sealed sample with volatile components, and a surface sample.

Mercury Dual Orbiter

Specially engineered for a hot environment, two spacecraft would study Mercury's magnetic origin, magnetosphere, atmosphere, ionosphere, surface, fields and particles, and solar physics.

Global Land/Ice Altimetry Mission

Using synthetic-aperture radar, this mission would obtain high-resolution elevation maps of the Earth's continents and ice caps for studies of geology, geophysics, volume and landforms in polar regions, and the terrestrial ecosystem.

Submillimeter Imaging and Line Survey

An Earth-orbiting telescope would allow physical and chemical studies of fast-moving galaxies, molecular clouds, star-forming regions, and planetary atmospheres in the submillimeter-wavelength region, beyond the far infrared.

Astrometric Imaging Telescope

This telescope, attached to the U.S. Space Station Freedom, would search for protoplanetary material or even large planets around nearby stars.

Large Deployable Reflector

A 10- to 20-meter- (33- to 66-foot-) diameter telescope would be deployed in high Earth orbit to study cosmology, galactic evolution, the interstellar medium, star formation, and protostars.

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Let thy speech be short, comprehending much in few words.

— Apocrypha: Ecclesiasticus

Chapter 15
Acronyms

An acronym is a word formed from the first letters of the words that make up a lengthy name or phrase. Some acronyms are so widely used that they have achieved the status of "real" words. A good example, and one that is near and dear to our Magellan hearts, is the word "radar," which actually means radio detection and ranging. As you can imagine, using this particular acronym within the Magellan Project is a real time-saver.

Acronyms are common in most endeavors all over the world; it's certainly a way of life at JPL, and the Magellan Project is no exception in this regard. However, the following list includes only those acronyms that appear in this Guide.

ALTA	altimeter antenna
ARUCAL	Attitude Reference Unit Calibration
Caltech	California Institute of Technology
C-BIDR	Compressed Basic Image Data Record
CD-ROM	Compact Disc-Read Only Memory
CDS	command and data subsystem
C1-MIDR	Compressed Once-Mosaicked Image Data Record
C2-MIDR	Compressed Twice-Mosaicked Image Data Record

C3-MIDR	Compressed Thrice-Mosaicked Image Data Record
DMAT	Data Management and Archive Team
DMS	Data Management Subsystem
DSCC	Deep Space Communications Complex
DSN	Deep Space Network
EDR	Experiment Data Record
ESA	European Space Agency
F-BIDR	Full-Resolution Basic Image Data Record
FEM	forward equipment module
F-MIDR	Full-Resolution Mosaicked Image Data Record
F-PIDR	Full-Resolution Polar Image Data Record
GCF	Ground Communications Facility
GDS	Ground Data System
GRAVIG	Gravity Investigation Group
HGA	high-gain antenna
HGACAL	High-Gain Antenna Calibration
IAU	International Astronomical Union
ICE	International Cometary Explorer
IDPS	Image Data Processing Subsystem
IOC	in-orbit checkout
IUS	Inertial Upper Stage
JPL	Jet Propulsion Laboratory
LGA	low-gain antenna
MCCC	Multimission Control and Computing Center
MCT	Mission Control Team
MGA	medium-gain antenna
MIDR	Mosaicked Image Data Record

MPT	Mission Planning Team
MSDT	Mission Sequence Design Team
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications (Network)
NAV	Navigation Team
NOCC	Network Operations Control Center
NSSDC	National Space Science Data Center
ODR	Original Data Record
OTM	orbit-trim maneuver
PDS	Planetary Data System
P-MIDR	Polar-Mosaicked Image Data Record
PSG	Project Science Group
PVO	Pioneer Venus Orbiter
RADIG	Radar Investigation Group
RCE	Reaction Control Equipment
RMSS	Radar Mapping Sequencing Software
RSET	Radar System Engineering Team
SAR	synthetic-aperture radar
SCT	Spacecraft Team
SDPS	SAR Data Processing Subsystem
SFCAL	Scale Factor Calibration
SFOC	Space Flight Operations Center
SRM	solid-rocket motor
STARCAL	star calibration
STS	Space Transportation System
TCM	trajectory-correction maneuver
VOI	Venus orbit insertion
VOIR	Venus Orbiting Imaging Radar
VRM	Venus Radar Mapper

I am known throughout the world as the Help-Bringer.

— Ovid

Chapter 16

Glossary of Geological Terms

The scientific results of the mapping phase of the mission will be reported by Magellan scientists in two ways: at press conferences (held at JPL), which are currently planned to begin in September 1990 and which will continue periodically throughout the 8-month mapping cycle, and eventually in articles published in science journals and popular science magazines.

The science results will focus primarily on the nature of the surface features of Venus and will necessarily include some terminology that is unfamiliar to those of us not educated in the field of geology. We hope the following list of basic geological terms will help decode some of the jargon. Within the definition of an entry, items set in boldface type are entries in this Glossary.

aa	A **basaltic** lava flow with a rough, jagged surface.
abyssal hill	A low, rounded submarine hill, with a relief of about 150 meters (492 feet), common in deep ocean basins.
angle of repose	The slope at which unconsolidated material remains stable.
anticline	A convex, upward-folded rock structure, with older rocks in the core and limbs that dip away from the **fold** axis.

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arachnoids	Spider-and-cobweblike features; 100-kilometer- (62-mile-) diameter circular structures on Venus, with a central volcanic feature surrounded by a complex network of **lineaments**.
asthenosphere	A worldwide layer below the **lithosphere**, composed of partially molten or liquid rock where **convection** may take place.
basalt	Fine-grained **igneous rock** (rich in **mafic** minerals) that has erupted onto the surface.
basement	The oldest rocks in a given area.
bedrock	Continuous solid rock that underlies **regolith** and is exposed at outcrops.
breccia	Coarse-grained rock composed of angular fragments of preexisting rock.
caldera	A large volcanic depression at the summit of a volcano, caused by collapse or explosion.
cinder cone	A conical hill formed of volcanic cinders.
compensation (isostasy)	A mechanism by which segments of the **crust** rise or sink to equilibrium positions, depending on the mass and density of the rocks above and below a certain depth called the depth of compensation.
convection	A mechanism of heat transfer from the interior to the exterior of a medium, in which hot material rises, because of its lower density, and cooler material sinks.
convergence zone	A band along which moving **plates** collide and area is lost either by shortening and crustal thickening or by **subduction** and destruction of **crust**. Convergence zones are sites of earthquakes, volcanism, trenches, and mountain building.
corona	A 170- to 1,000-kilometer- (106- to 621-mile-) diameter circular-to-elongate Venusian feature surrounded by multiple concentric ridges, thought to be formed by **hot spots**.

crater	An abrupt circular depression formed by extrusion of volcanic material and its deposition in a surrounding rim, or by explosive ejection of material on **meteorite** impact.
cross-cutting relationship principle	The principle that a rock is younger than any rock across which it cuts.
crust	The outermost layer of the **lithosphere**.
crustal spreading	A mechanism by which new **crust** is created at ridges in **divergence zones** and adjacent **plates** move apart to make room.
degradation	A general lowering of the surface by processes of erosion.
differentiated planet	A planet where heavier materials have sunken to the center and lighter materials have accumulated in the **crust**.
dike	A roughly planar body of intrusive **igneous rock**.
dip	The angle that a surface makes with the horizontal, measured perpendicular to the **strike**.
discontinuity	A physical interruption in a sequence or distribution of strata (layers of rock).
divergence zone	A belt along which **plates** move apart and new **crust** and **lithosphere** are created. Divergence zones are sites of midocean ridges, earthquakes, and volcanism.
ductile	Capable of considerable deformation or change in shape without breaking.
dune	An elongate mound of sand formed by wind or water.
en echelon	A steplike arrangement of features.
endogenic	Of or relating to a geologic process originating within a planet.

ejecta — Material thrown out of a volcano or impact **crater**.

eolian — Related to wind deposits and associated effects.

fault — A fracture or zone of fractures in a planet's **crust**, accompanied by displacement of the opposing sides. Faults are classified according to the direction of relative movement:

(1) normal	A hanging wall has moved down relative to a footwall.
(2) reverse	A hanging wall has moved up relative to a footwall.
(3) thrust	A low-angle reverse fault where the **dip** of the fault plane is below 45 degrees.
(4) strike-slip	Movement is parallel to the **strike** of the fault.
(5) transform	A special type of **strike-slip** fault forming the boundary between two moving lithospheric plates, usually along an offset segment of the oceanic ridge.

flood basalt — Extensive, high-volume **basaltic** lava flows erupted from fissures.

fluvial — Relating to a river or rivers.

fold — The product of the deformation of planar rock bodies.

footwall — A block beneath a dipping **fault** surface.

fracture zone — A zone of long, linear fractures expressed topographically by ridges and **troughs**; the surface expression of a **transform fault**.

graben — A depressed, elongate crustal block bounded by **normal faults** along its sides and produced by extensional forces.

granite — Coarse-grained intrusive or plutonic **igneous rock** composed mostly of quartz and feldspar.

gravitational relaxation	A process by which rocks behave **ductilely** and flow on relatively short geologic time scales (hundreds of millions of years), resulting in the lowering of topographic relief.
greenhouse effect	The heating of the atmosphere by the absorption of infrared energy reemitted by a planet as it receives light energy in the visible band from the Sun.
hanging wall	A block above a dipping **fault** surface.
horst	An uplifted, elongate crustal block bounded by **reverse faults** along its sides.
hot spot	A persistent volcanic center thought to be the surface expression of a rising hot **mantle plume**.
igneous rock	Rock solidified from a molten state.
ignimbrite	**Igneous rock** formed by widespread deposition and welding of ash flows.
intrusion	An **igneous rock** body that, when in a molten state, forced its way into the surrounding rock.
lineament	A linear feature that may depict crustal structure.
lithosphere	The relatively strong outer layer of a planet that includes the **crust** and part of the upper **mantle**.
mafic	Relating to rock or **magma** comparatively rich in iron and magnesium silicates.
magma	Molten rock material (liquids and gases).
mantle	The main bulk of a planet between the **crust** and the core; on Earth, the mantle ranges from about 40 to 2,900 kilometers (25 to 180 miles) below the surface.
mare	A dark, low-lying lunar plain, filled to some depth with volcanic rocks.
melange	A formation consisting of a heterogeneous mixture of rock materials intermingled and consolidated by tremendous deformational pressure.

meteorite	A stony or metallic object from interplanetary space that impacts a planetary surface.
multiringed basin	A large impact **crater** containing a series of concentric ridges and depressions (e.g., the Orientale Basin on the Moon).
orogeny	The process of mountain building.
pahoehoe	A **basaltic** lava flow with a smooth, undulating surface.
partial melting	The process by which minerals with low melting points liquify within a rock body as the result of an increase in temperature and/or a decrease in pressure, while other minerals in the rock body are still solid.
plate	A broad segment of the **lithosphere** (the rigid upper **mantle** plus the **crust**) that floats on the underlying **asthenosphere** and moves independently of other plates.
plate tectonics	The theory and study of **plate** formation, movement, interaction, and destruction. This theory attempts to explain volcanism, seismic activity (earthquakes), mountain building, and paleomagnetic data in terms of plate motions.
plume (hot spot)	A rising, buoyant mass of hot, partially molten **mantle** material that rises to the base of the **lithosphere**.
pluton	A large **igneous rock** intrusion formed at depth in the **crust**.
pyroclast	Fragmental material ejected by a volcanic eruption.
regolith	Any solid material lying on top of **bedrock**, including soil and rock fragments.
relative age/ relative dating	The age of a rock or event compared with those of other rocks or events without reference to years; a geologic determination based on **superposition** and **cross-cutting relationships**.

relief	The maximum regional difference in elevation.
rheology	The physical properties that govern the flow characteristics of solid material.
rift	A valley formed at a **divergence zone** or other area of extension.
scarp	A cliff or steep slope of some extent that may form a marked topographic boundary.
shield volcano	A broad volcanic cone with gentle slopes constructed of successive nonviscous, mostly **basaltic**, lava flows.
silicic	Relating to rock or **magma** comparatively rich in aluminum and potassium silicates.
spreading center	See **crustal spreading**.
strike	The horizontal direction of a structural surface.
subduction	The process of one lithospheric plate descending beneath another.
superposition principle	The principle that, except in extremely deformed rock, a rocky unit that overlies another rocky unit is always younger.
syncline	A concave folded rock structure with younger rocks in the core and limbs that dip toward the **fold** axis.
talus	A deposit of large, angular rock fragments of eroded **bedrock** at the base of a cliff or steep slope.
tectonic	Pertaining to structural and deformational features in a planet's **crust** and to the forces that produce such features.
terrain	A physical region or feature.
terrane	A region where a particular rock or rock group predominates.
tesserae	Complex, deformed **terrain** on Venus consisting of at least two sets of intersecting ridges and **troughs**.

topography	The shape and form of the surface of a planet.
trough	A long linear depression.
vent	An opening or fissure in a planet's surface through which volcanic material erupts.
viscosity	A measure of resistance to flow.
volcanic rock	Rock formed by eruption in a planet's surface.

Sources:

F. Press and R. Siever, *Earth*, San Francisco, W. H. Freeman and Company, 1978.

W. K. Hamblin, *The Earth's Dynamic Systems*, Minneapolis, Burgess Publishing Company, 1985.

American Geological Institute, *Dictionary of Geological Terms*, New York, Anchor Press, 1976.

To you! To you! all song of praise is due.

— Sir Philip Sidney

Chapter 17
Acknowledgment

Many people within and outside the Magellan Project wrote, verified, and reviewed the text in this Guide. We thank them for the quality of their contributions and for incorporating our deadlines into their busy schedules.

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